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ANALYSIS OF SUBARRAY WAVENUMBER SPECTRA

Special Scientific Report No. 6

LARGE-ARRAY SIGNAL AND NOISE ANALYSIS

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Prepared by

Donald B. Crouch

Frank H. Binder, Program Manager

TEXAS INSTRUMENTS INCORPORATED
Science Services Division
P.O. Box 5621
Dallas, Texas 75222

Contract No. AF 33(657)-16678

Prepared for

AIR FORCE TECHNICAL APPLICATIONS CENTER
Washington, D.C. 20333

Sponsored by

ADVANCED RESEARCH PROJECTS AGENCY
ARPA Order No. 599
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VELA Seismological Center
Hq. USAF, Wash. D.C.

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ABSTRACT

The ambient seismic noise at LASA was studied using high-resolution wavenumber spectra obtained for several subarrays chosen from seven noise samples covering a seven month period. A comparison of the high-resolution spectra with conventional spectra measured at two subarrays for one of the noise samples was made.

Estimations of the frequency power spectra of the mantle P-wave noise and isotropic Rayleigh-wave energy were obtained. Also, estimations of the power spectra were determined for two low-velocity ($V < 8.0$ km/sec), fairly time-stationary, directional noise modes. One mode was present at 0.2 cps only, and the other was evident in the frequency range 0.8 to 1.1 cps.

This investigation of the ambient seismic noise revealed one outstanding difference between the characteristics of subarray F1 and the characteristics of the other six subarrays studied. At 0.3 cps the apparent velocity (1.6 km/sec) of isotropic surface-mode energy at F1 was lower than the velocity of this energy (2.2 km/sec to 2.7 km/sec) at the other subarrays.

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SECTION I

INTRODUCTION AND SUMMARY

This report presents the results of an investigation of ambient seismic noise at LASA. Essentially, the analysis is based on high-resolution wavenumber spectra obtained for several subarrays chosen from seven noise samples recorded from October 1965 through April 1966. One set of conventional wavenumber spectra for two subarrays was calculated also.

Major results of the analysis of these spectra are

- Estimation of the frequency power spectrum of the mantle P-wave noise.
- Separation of isotropic Rayleigh-wave energy and an estimation of its power spectrum in the 0.3-to 0.6-cps frequency range.
- Separation of an organized noise mode in the frequency range 0.8 to 1.1 cps propagating at 4.0 to 5.0 km/sec from a northeasterly direction.
- Separation of fairly time-stationary, low-velocity (3.0 to 4.0 km/sec) noise at 0.2 cps. This noise was interpreted as higher-order surface-mode energy traveling from an area extending N42°E to N80°E.
- Detection of a characteristic of subarray F1, which is different from the general features of the other subarrays. The apparent velocity of isotropic surface-mode energy at low frequencies (around 0.3 cps) was about 1.6 km/sec at subarray F1 but was 2.2 to 2.7 km/sec at the other subarrays investigated.

SECTION II

INTERPRETATION OF CONVENTIONAL WAVENUMBER SPECTRA

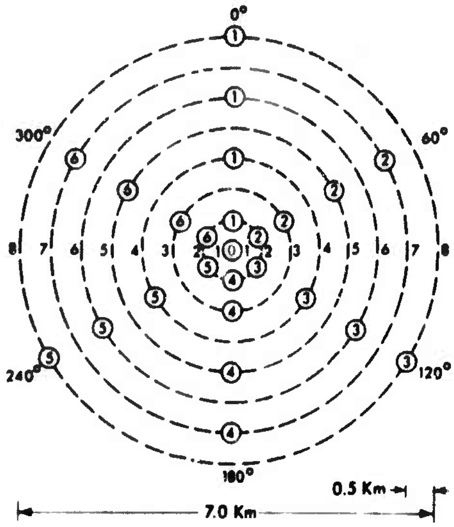
Conventional wavenumber spectra of a noise sample recorded on 25 March 1966 from 04:34:13.1 to 04:42:13.0 were measured for subarrays B1 and C2 at 0.2 cps and at frequencies from 0.3 to 1.1 cps in increments of 0.2 cps. Only the 19 seismometers in rings 1, 3, 4, 5, 6, 7, and 8 (Figure II-1) were used. A limitation in a computer program forced this restriction. The wavenumber spectra were obtained by expanding the array data in correlation space and then taking the 2-dimensional Fourier transform.

Figure II-2 shows the wavenumber spectra measured at subarrays B1 and C2 at 0.2 cps. The spectral window at 0.2 cps is included in the figure also. Estimates of the spectra are similar for both subarrays. The noise appears to be predominantly high velocity (V > 8.0 km/sec), but the resolving power of the subarray is not sufficient to show any peaks.

Likewise, at 0.3 cps (Figure II-3), both subarrays have poor resolution. Both wavenumber spectra indicate dominant high-velocity energy.

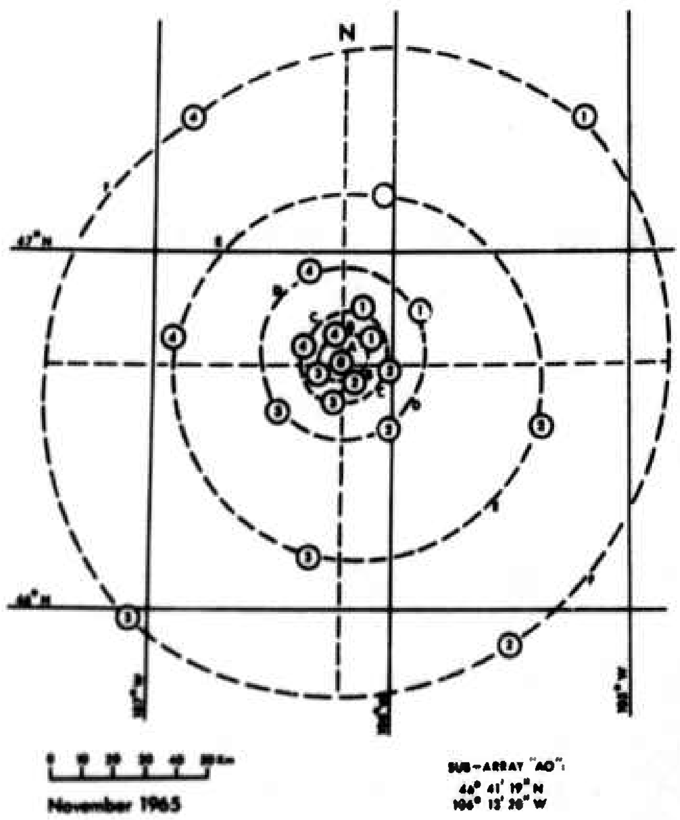
Wavenumber spectra at 0.5 cps measured at subarrays B1 and C2 and the spectral window at 0.5 cps are shown in Figure II-4. Again, the spectral estimates are consistent, and the high-velocity noise predominates. The similarity of the spectral window and the wavenumber spectra indicates a strong peak near infinite velocity.

At 0.7 cps, wavenumber spectra measured at both subarrays also have similar characteristics (Figure II-5). The noise field is more complex at this frequency than at lower frequencies. In addition to the high-velocity noise, there are indications of a lower-velocity (V >8.0 km/sec) noise mode propagating roughly from the east.



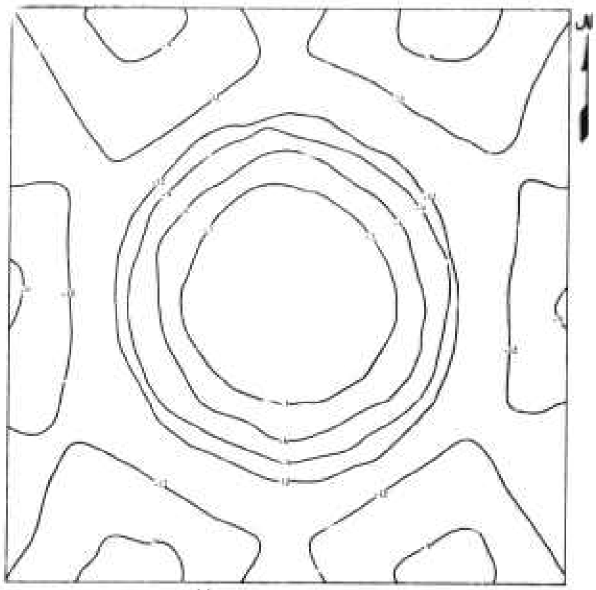
STANDARD SUBARRAY

NOTE:
Seismometer No. 10 Is 500' Deep
Seismometers 21-65 Are 200' Deep

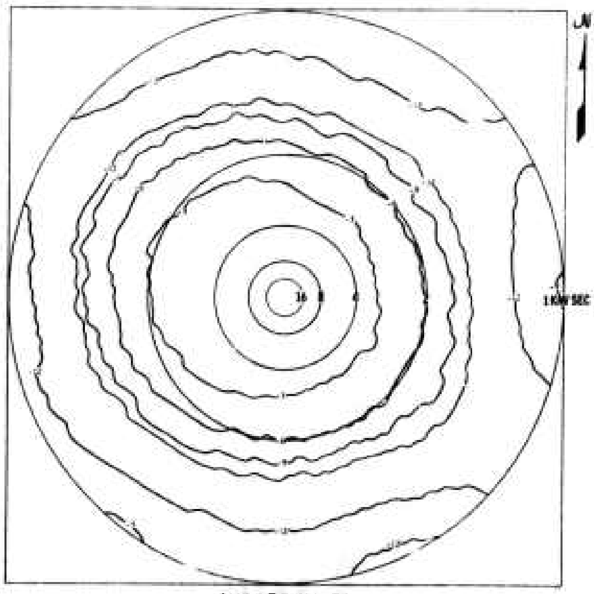


LASA

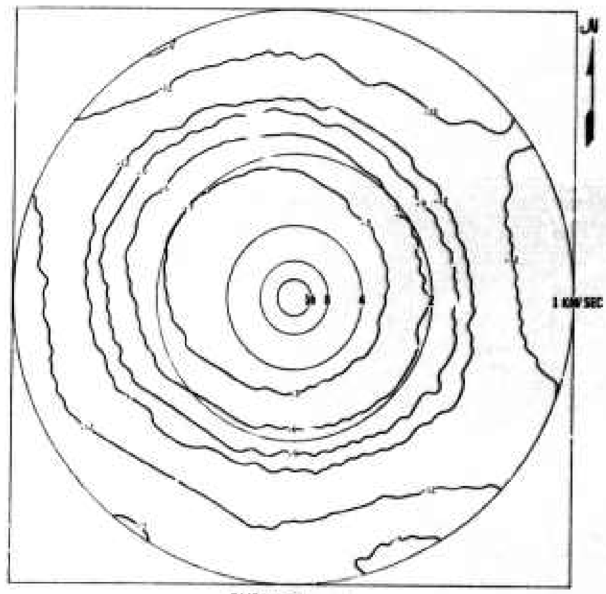
Figure II-1. LASA Standard Subarray



SPECTRAL WINDOW



SUBARRAY B1



SUBARRAY C2

Figure II-2. Subarray Wavenumber Spectra at 0.2 cps

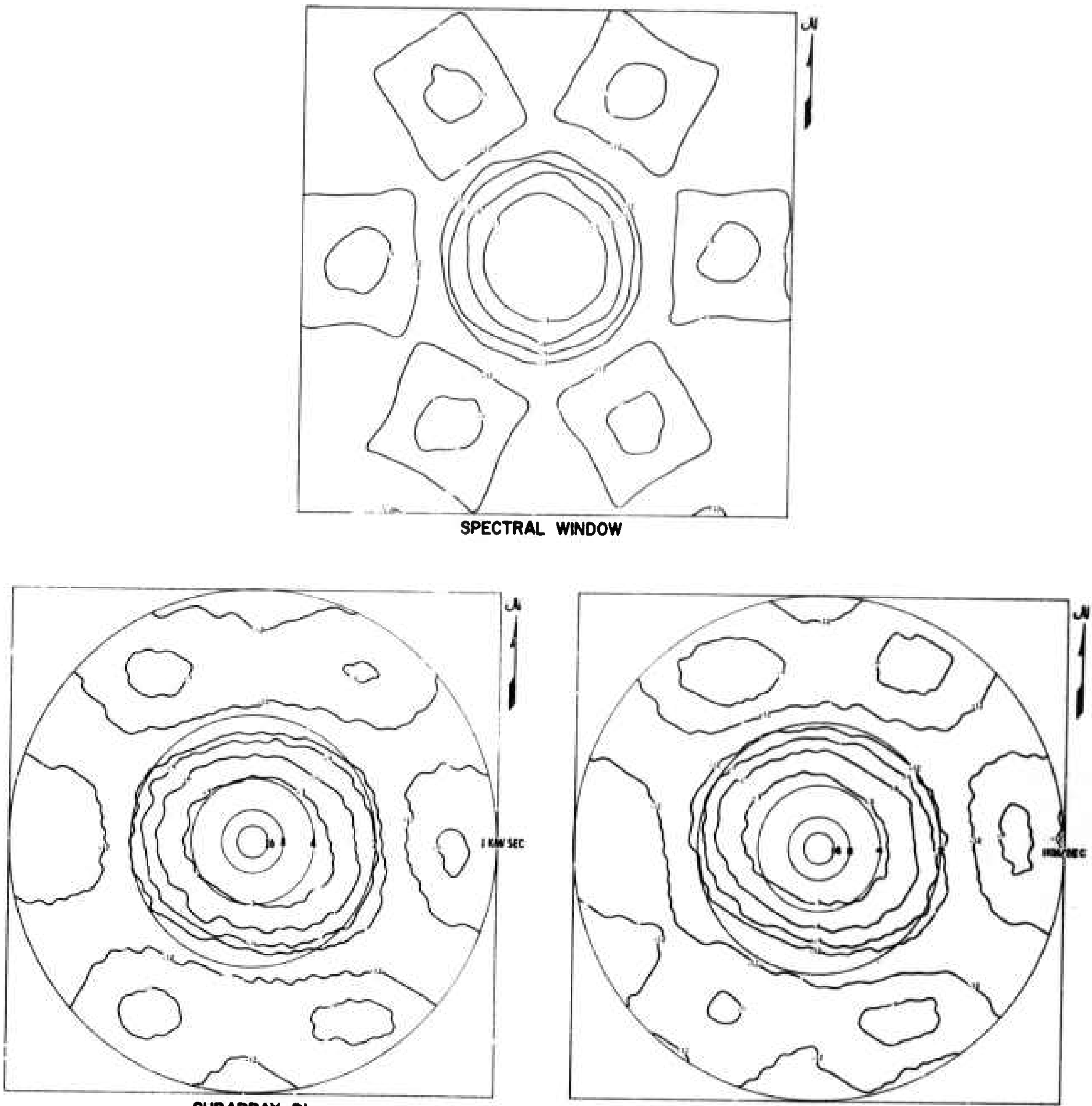


Figure II-3. Subarray Wavenumber Spectra at 0.3 cps

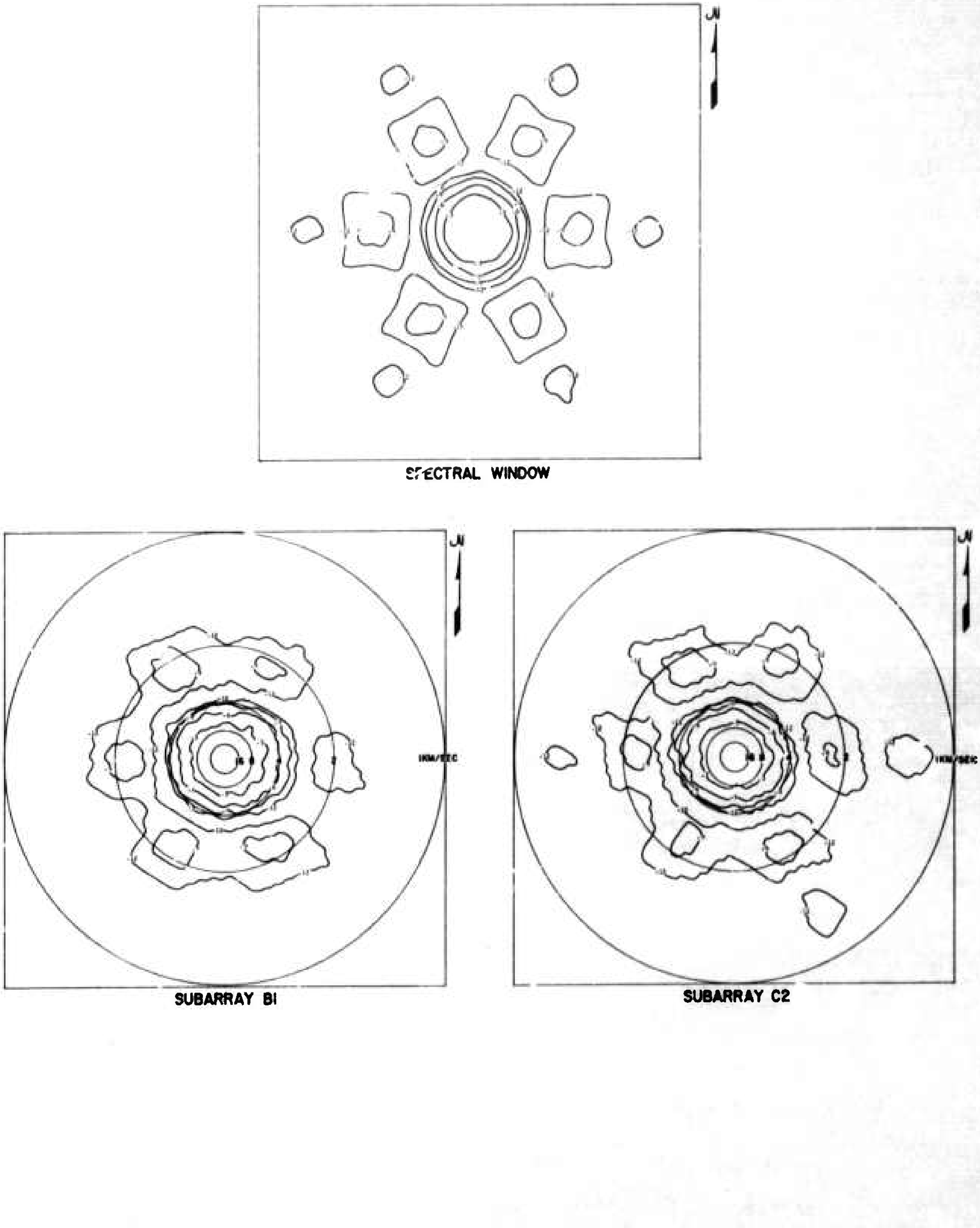


Figure II-4. Subarray Wavenumber Spectra at 0.5 cps

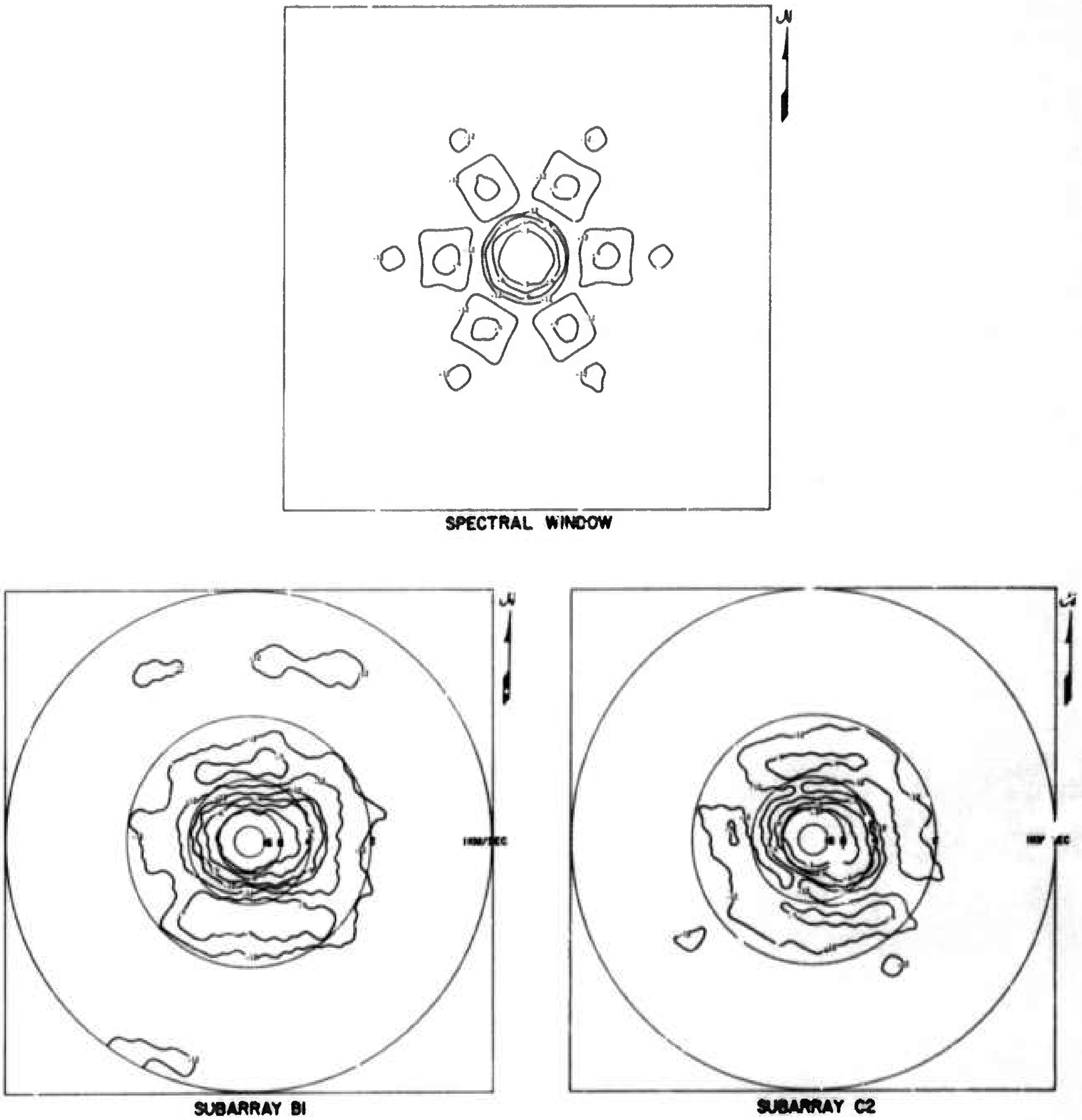


Figure II-5. Subarray Wavenumber Spectra at 0.7 cps

There is a better indication of this strong low-velocity peak in the wavenumber spectra of B1 and C2 at 0.9 cps (Figure II-6). The noise mode appears to be traveling from the east with a velocity of 4.0 to 8.0 km/sec. The P-wave peak and the lower-velocity peak are not separated, which makes velocity estimation difficult. Spectra for the two subarrays are again very similar.

Figure II-7 shows the wavenumber spectra and the spectral window at 1.1 cps. The coherent noise is dominated by the low-velocity westerly propagating noise and by high-velocity noise.

At 1.3 cps (Figure II-8), dominant features of the wavenumber spectra measured at 1.3 cps are similar. The coherent noise has a sharp peak corresponding to wave propagation from the east at about 8.0 km/sec. The outlying peaks are probably meaningless because of the strong random components at this frequency.

At each frequency, there was general agreement in the wavenumber spectra measured at B1 and C2 subarrays. The low-frequency noise (below 0.7 cps) is dominated by high-velocity ($V > 8.0$ km/sec) energy. There appears to be some organized lower-velocity noise above 0.7 cps.

One-dimensional spectra measured at three other subarrays for this noise sample also contained a noise mode propagating from N79°E to S88°E with a velocity of 4.0 to 5.0 km/sec. These K-line spectra are discussed and a comparison with the conventional spectra is made in Section IV.

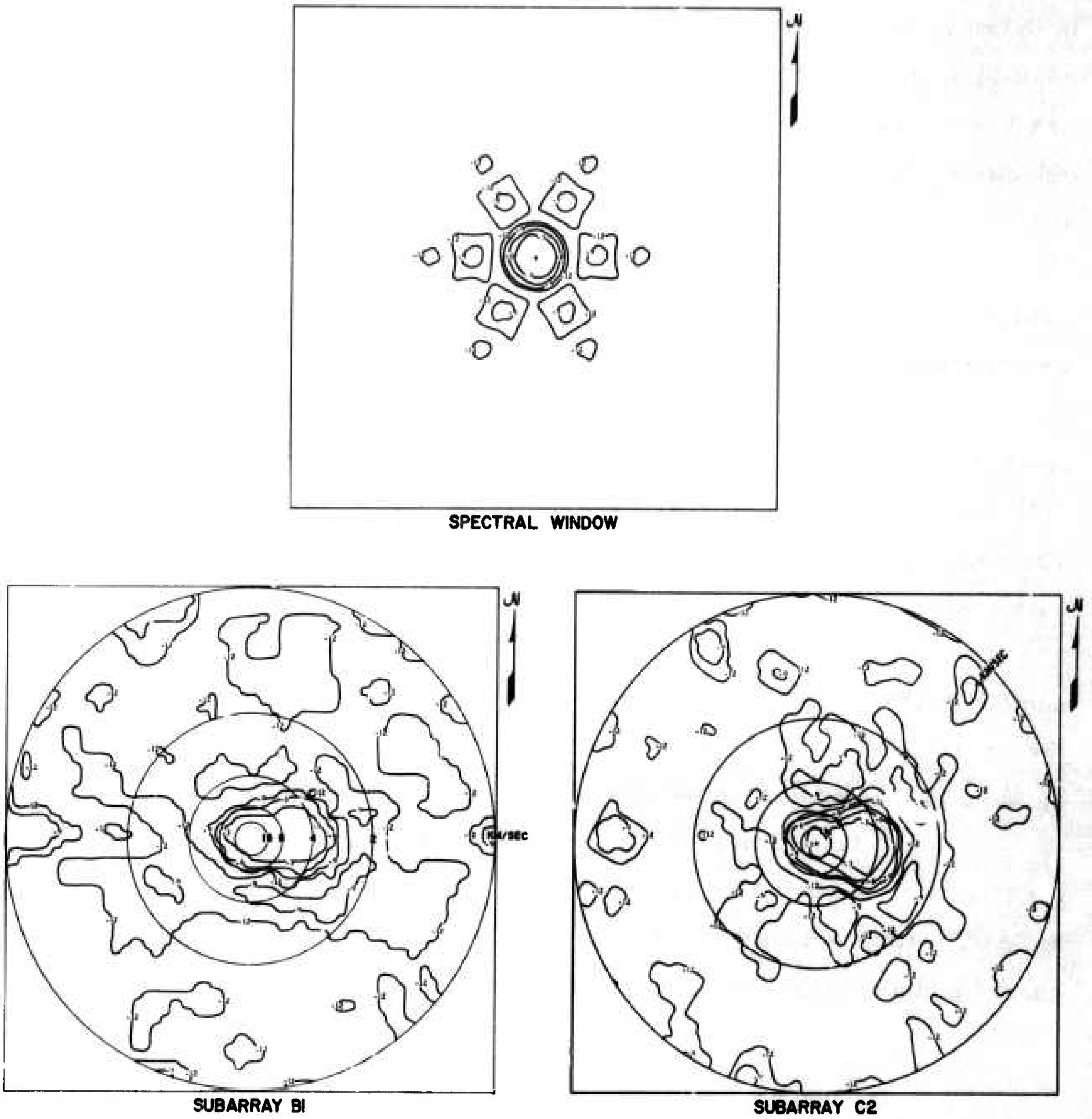


Figure II-6. Subarray Wavenumber Spectra at 0.9 cps

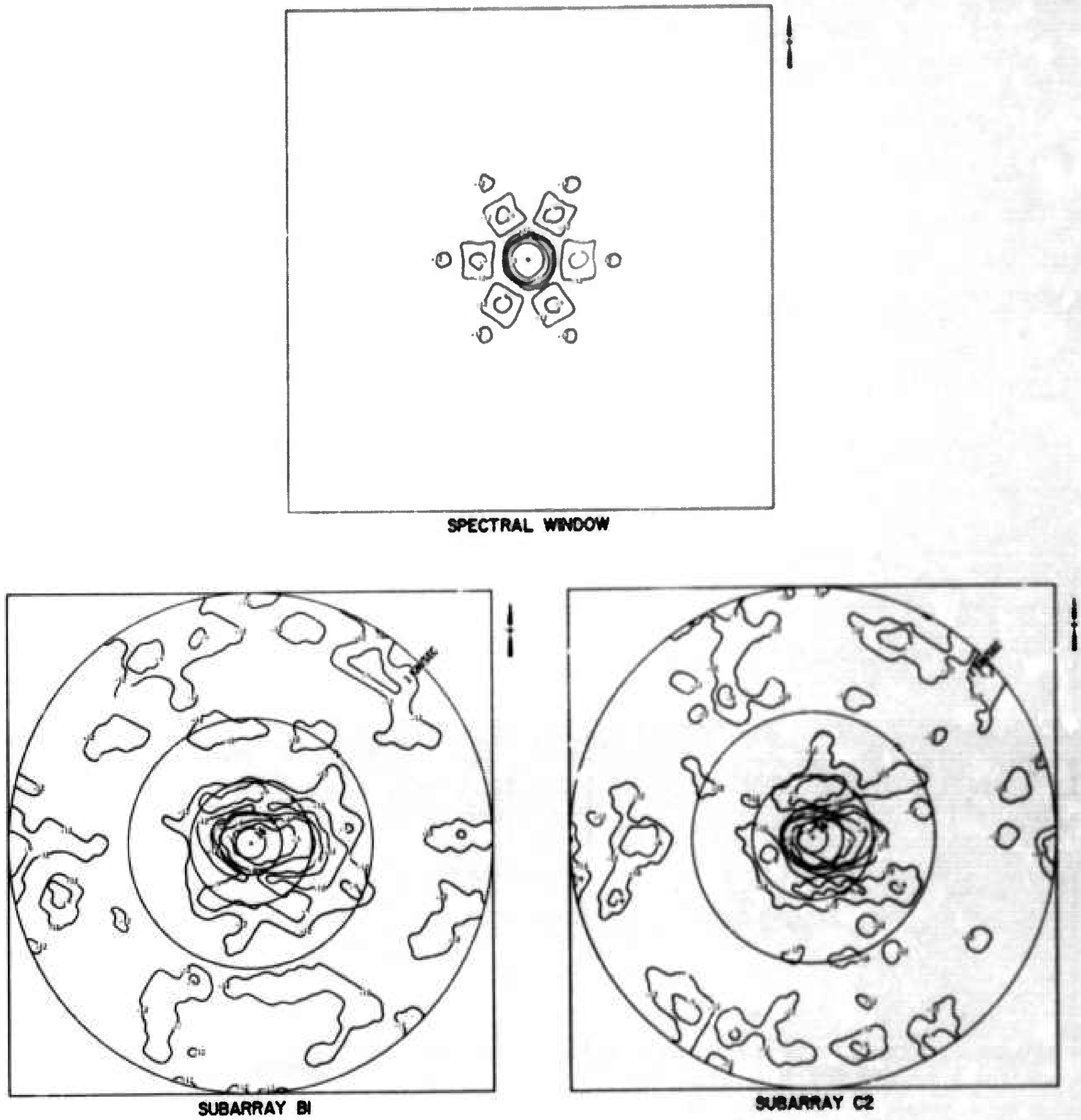


Figure II-7. Subarray Wavenumber Spectra at 1.1 cps

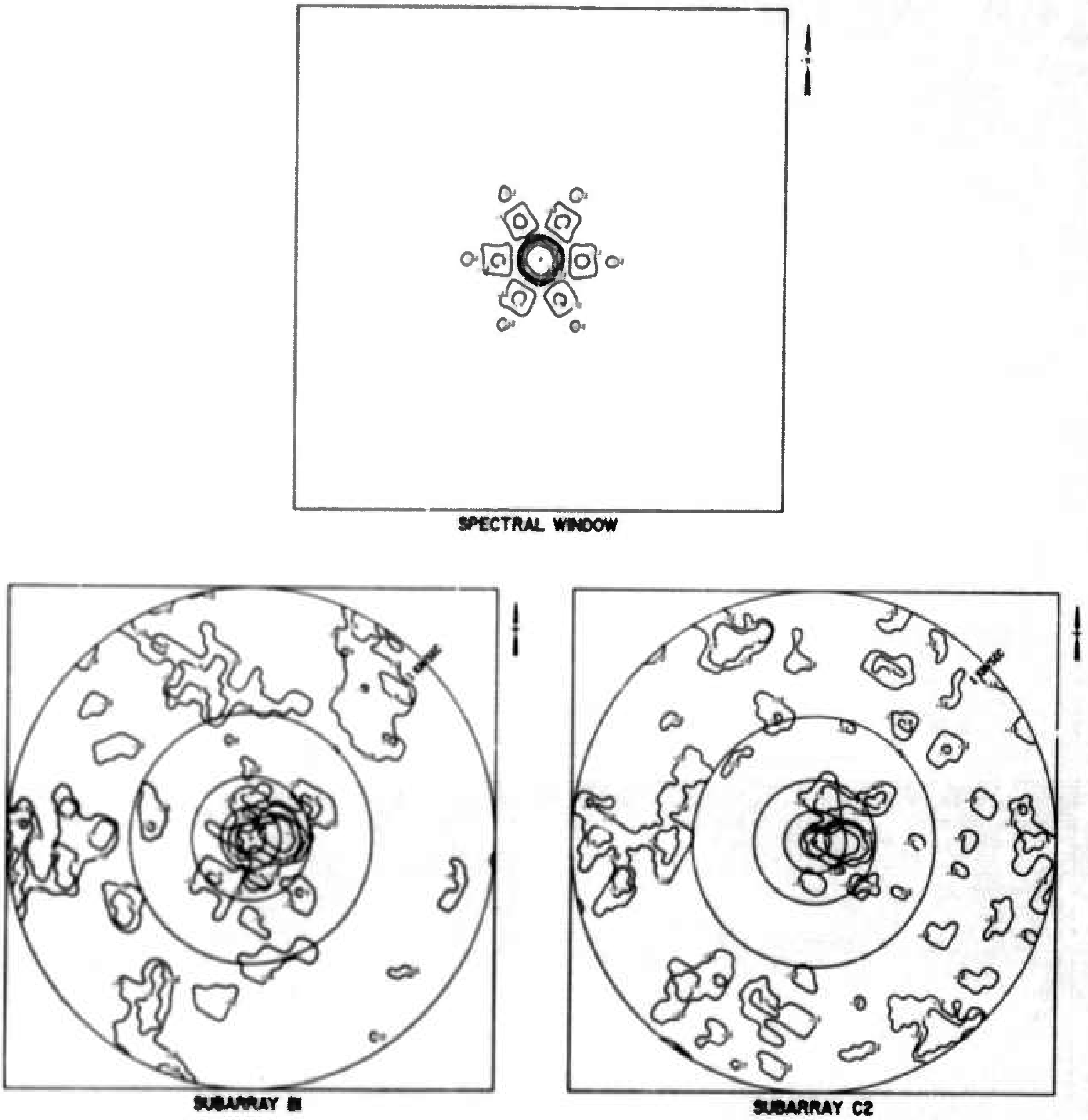


Figure II-8. Subarray Wavenumber Spectra at 1.3 cps

SECTION III

DESCRIPTION OF THE K-LINE WAVENUMBER SPECTRA

A general description of the K-line wavenumber spectra has been presented in previous literature,[1] but a brief description is included here for the reader's convenience.

The 1-dimensional wavenumber spectra are physically interpreted as projections of 2-dimensional power-density spectra onto axes which are parallel to the axes of a LASA subarray (Figure II-1). These spectra give the power density of the ambient seismic noise as a function of its apparent wavenumber along each of the array's arms. Although knowledge of the spectral projections onto the three arms is basically inferior to knowing the 2-dimensional spectrum itself, the resolution of these K-line spectra provides a much higher resolution spectrum of the LASA noise field than is obtainable using only the low-resolution 2-dimensional spectra.

The basic input for calculating each of the 1-dimensional spectra is the crosspower matrix $[\Phi_{ij}(f)]$, where f is the frequency and i and j range over the seismometers of each arm of the array. The cross-power matrices were obtained by transforming the time traces using the Cooley-Tukey algorithm[2] and smoothing the weighted crossproducts of the Fourier transform outputs over a 0.1-cps frequency interval (41 basic frequency points).

K-line wavenumber spectra were calculated in increments of 0.1 cps at ten frequencies starting with 0.2 cps. These sets of spectra were measured at various subarrays for seven noise samples. The spectra are shown in Figures III-1 through III-16.

For each frequency, there is a wavenumber power-density spectrum and an integrated wavenumber power-density function for each line of the array. The power-density spectrum and the integrated density function are included in the same plot to save space. Wavenumber spectra are plotted in db vs wavenumber in cycles/km. The left vertical axis is marked in 5-db increments with the 0-db level indicating the average value of the spectrum.

The normalized, integrated wavenumber power-density function is

$$\int_{-k}^{x} P(x)dx, \text{ with } \int_{-k}^{k} P(x)dx = 1$$

where P(x) is the wavenumber power-density spectrum and k is the foldover wavenumber. The foldover wavenumber is 1 ÷ 2 times the average spacing of the equidistant seismometers along the arm of the array. This function has been plotted in fractional power vs wavenumber in cycles/km. The right vertical axis is marked from 0.0 to 1.0 in increments of 0.1. These integrated spectra provide a method of measuring the amount of power in any velocity or wavenumber band.

In these wavenumber plots, the solid vertical line at the center of the plot (at k = 0) represents infinite apparent velocity along the arm of the array. On either side of this line are dashed lines representing velocities of 8.0 km/sec and 1.6 km/sec. These velocities are approximately the minimum apparent velocities for P-wave and Rayleigh-wave noise when the noise propagation is in-line with an arm.

The velocity of 1.6 km/sec is the approximate fundamental surface-mode velocity in the frequency range 0.3 cps $<f<$1.0 cps. The Rayleigh-wave velocity lines (1.6 km/sec) correspond to the edge velocity of the plots at 0.8 cps. At higher frequencies, the velocity lines appear in their aliased position.

The third function contained in each plot is a discrete function denoted by small x's. These x's show the fractional power that is unpredictable when one tries to predict the next seismometer in line from a line of seismometers. In particular, the first x from the right is the fractional mean-square error in predicting one seismometer ahead (1.0 km) using four seismometers in a line. The first x to the left of the edge of the plot shows the prediction error using only one seismometer. The right vertical axis, marked from 0.0 to 1.0 in increments of 0.1, is used to determine the prediction error corresponding to each x.

Figure III-17 shows the fractional prediction error in db as a function of frequency (using four seismometers to predict the fifth) for each arm of each subarray for all noise samples. Since the prediction error at TFO (using 10 seismometers to predict the eleventh) is about the same as the prediction error using four seismometers to predict the fifth,[1] a comparison of the prediction error at TFO with the prediction error at LASA was made. Fractional prediction error at LASA is, on the average, 3.5 to 7.5 db greater that the prediction error at TFO in the frequency range 0.3 to 0.8 cps. At all other frequencies, the difference is less than 1.0 db.

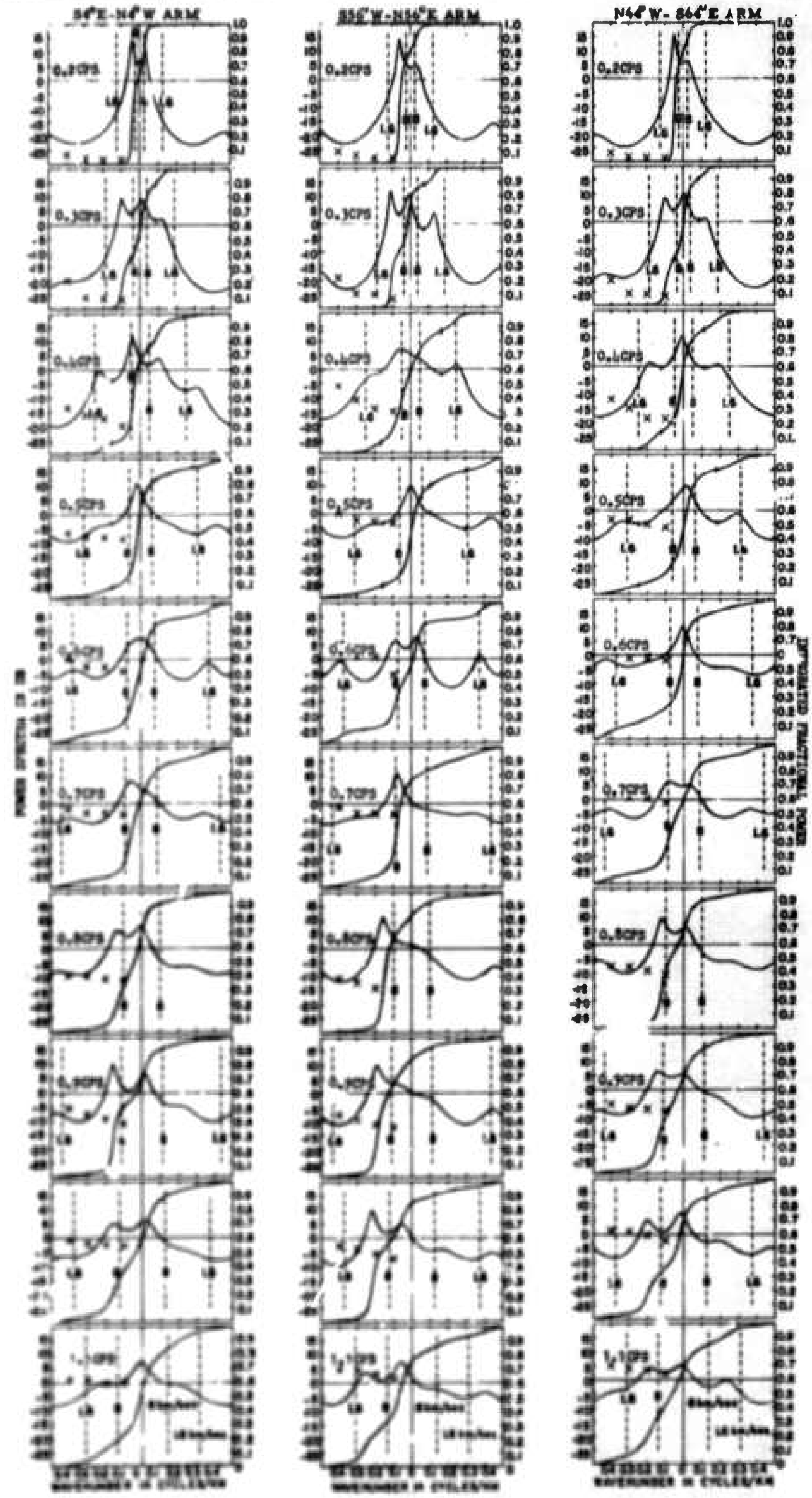


Figure III-1. Wavenumber and Integrated Spectra for Subarray A0 for 29 October 1965

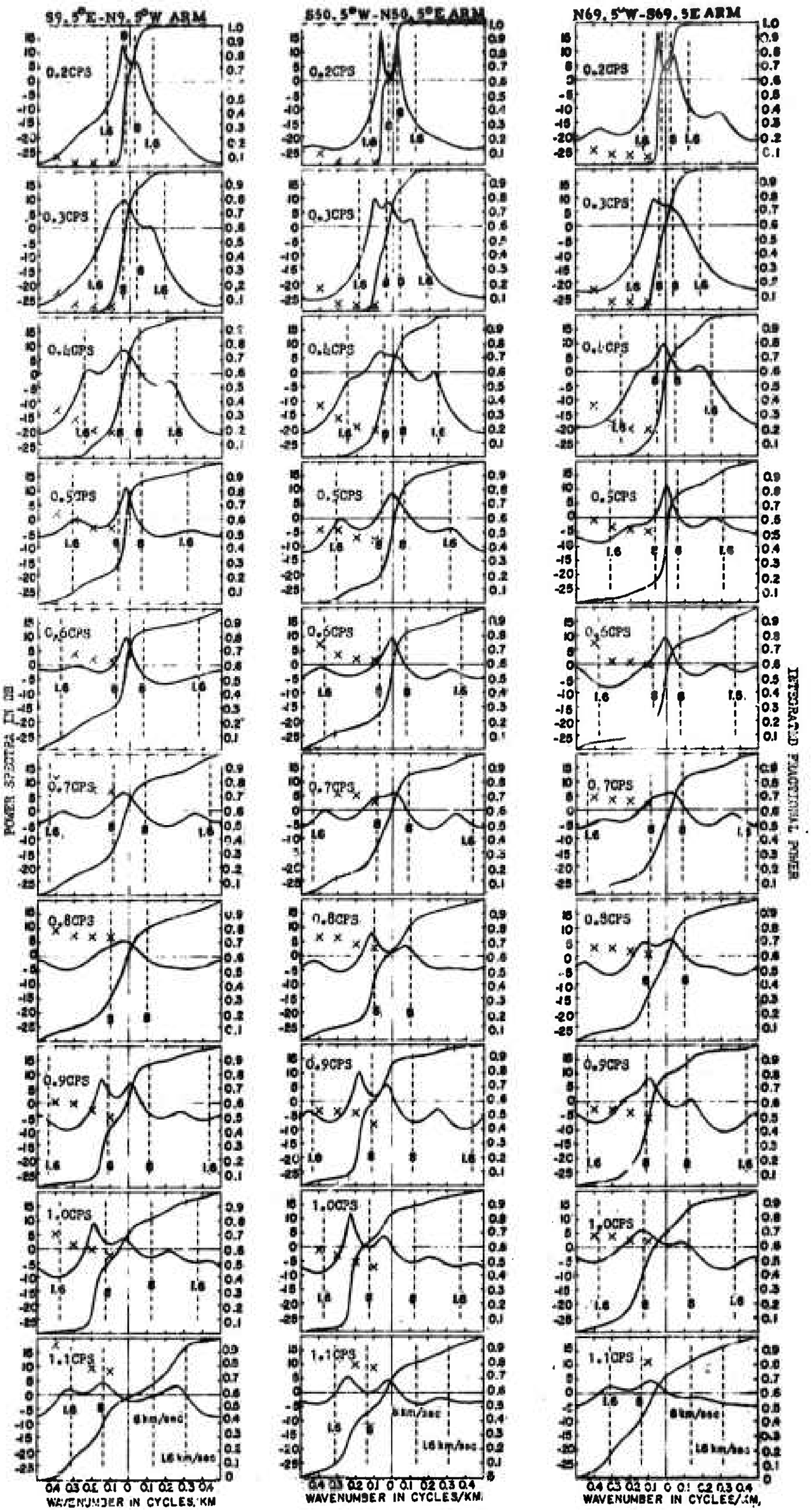


Figure III-2. Wavenumber and Integrated Spectra for Subarray F4 for 29 October 1965

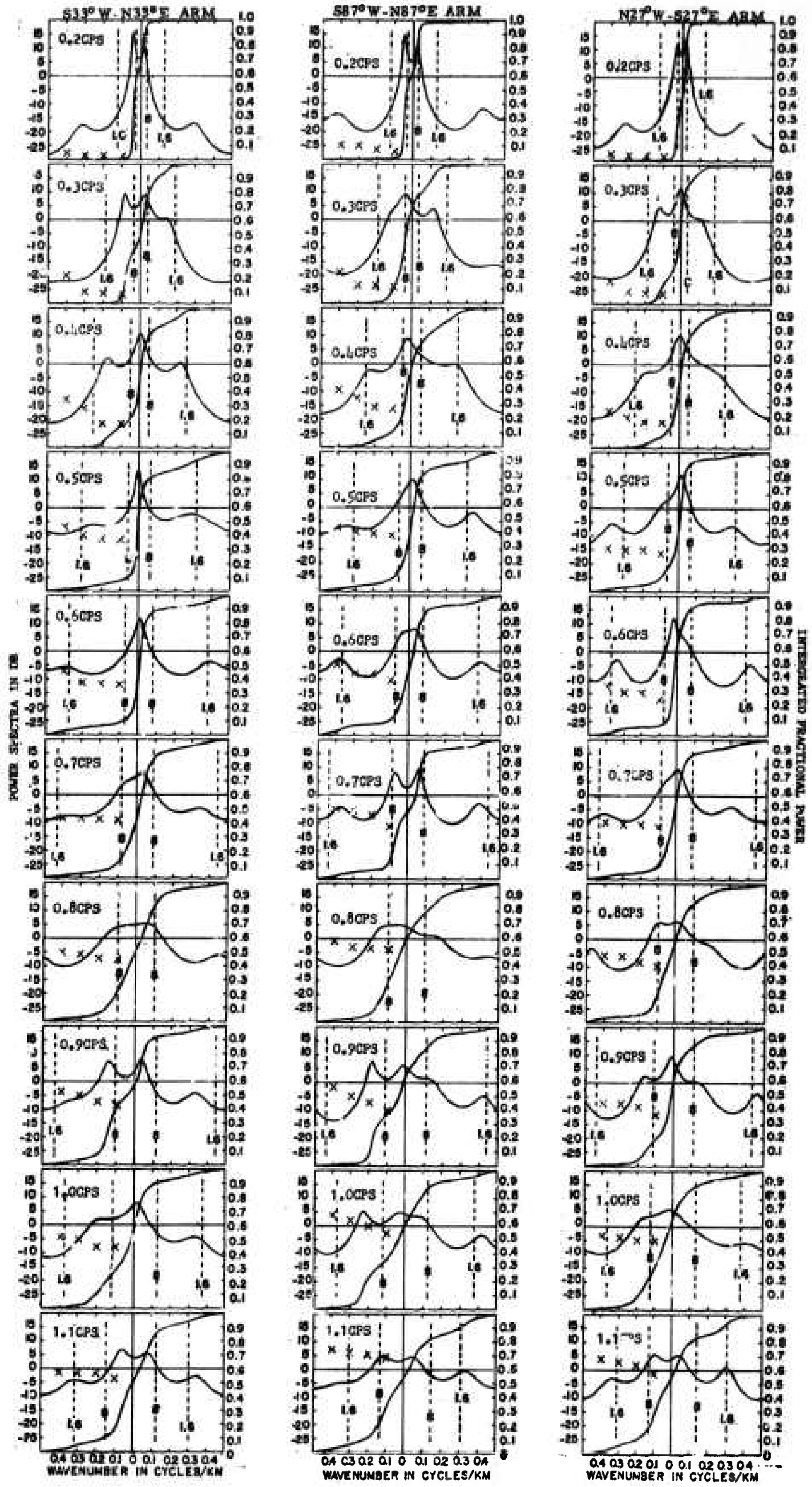


Figure III-3. Wavenumber and Integrated Spectra for Subarray B3 for 22 January 1966

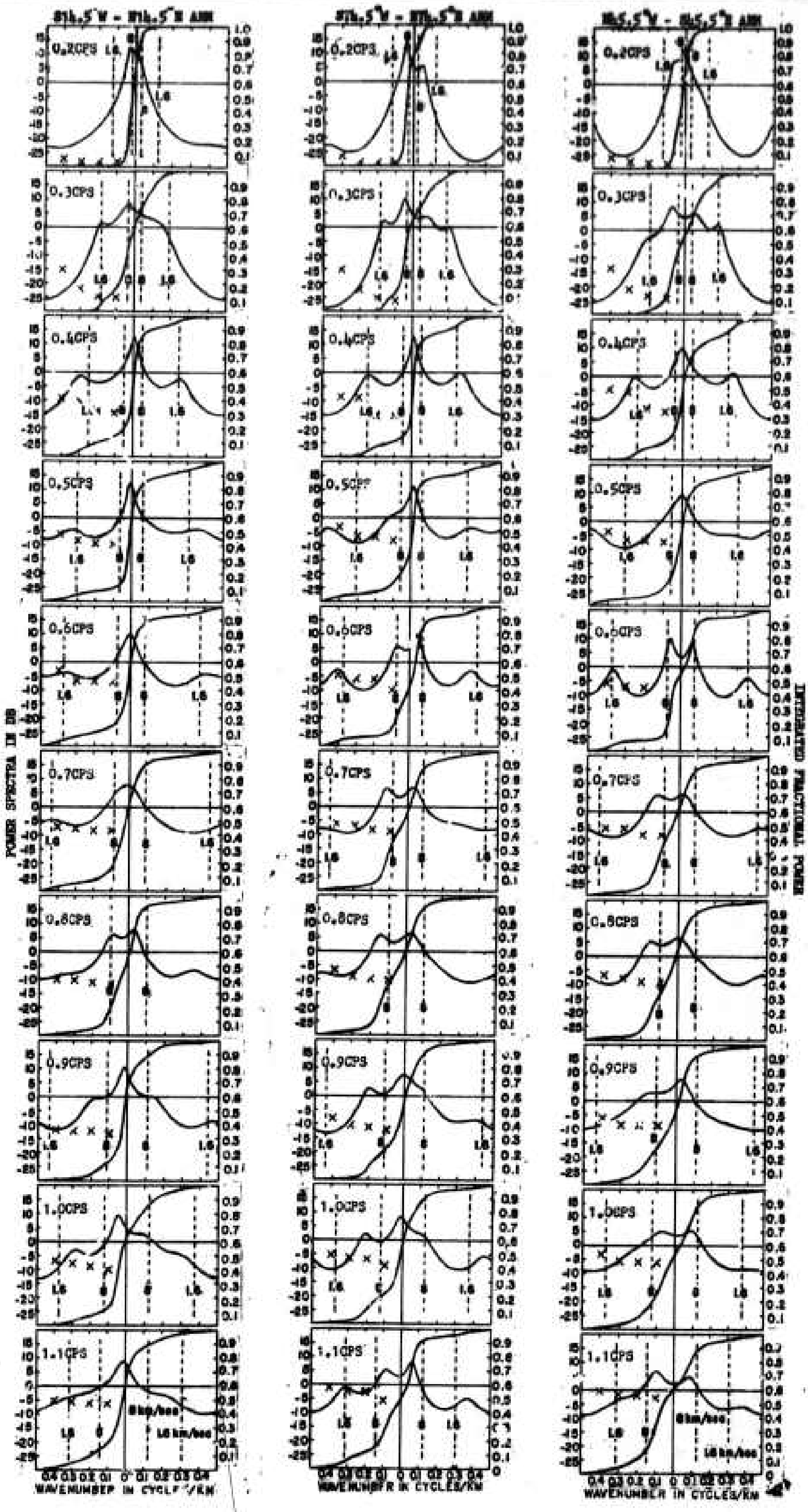


Figure III-4. Wavenumber and Integrated Spectra for Subarray F1 for 22 January 1966

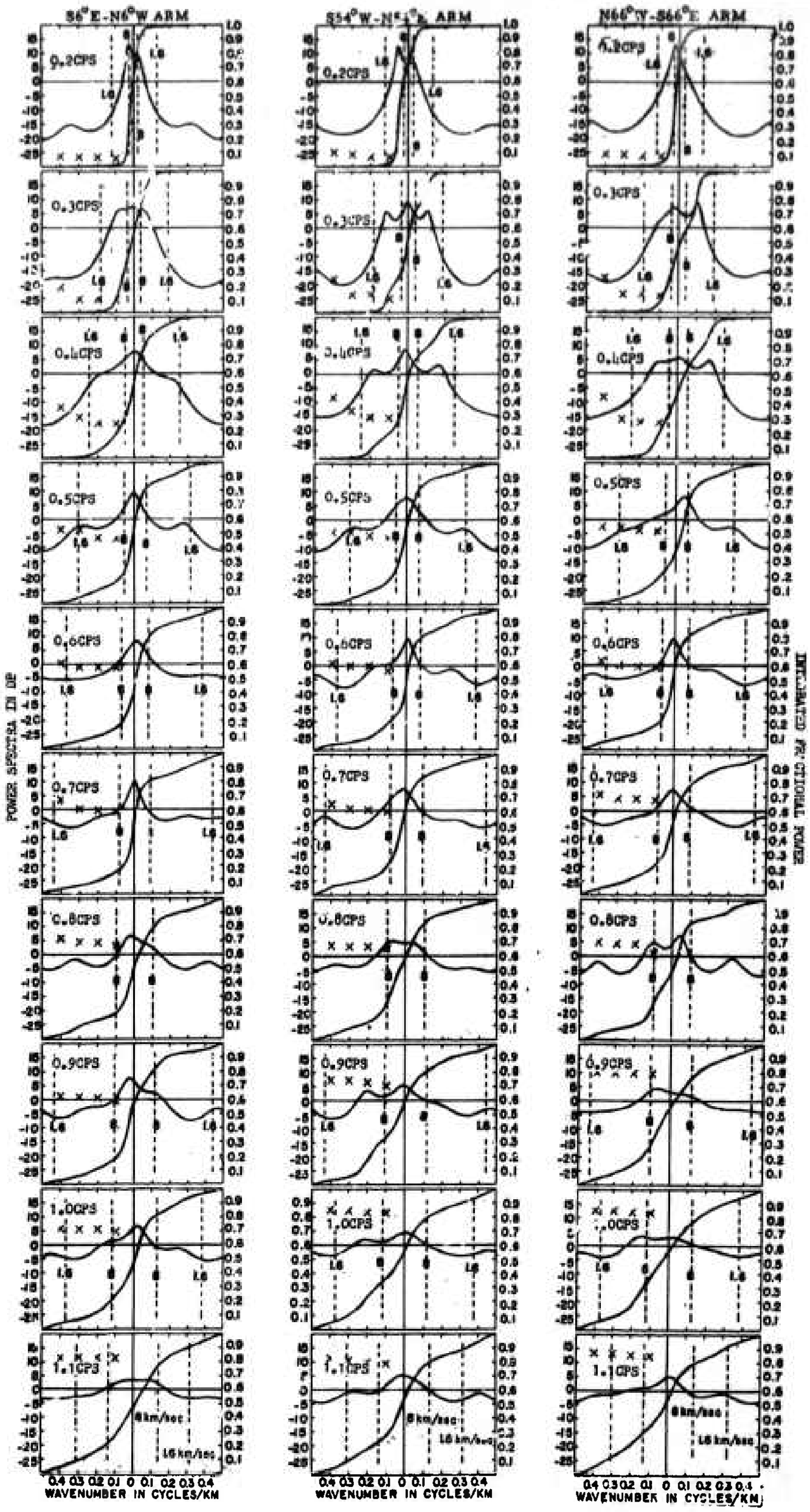


Figure III-5. Wavenumber and Integrated Spectra for Subarray F3 for 22 January 1966

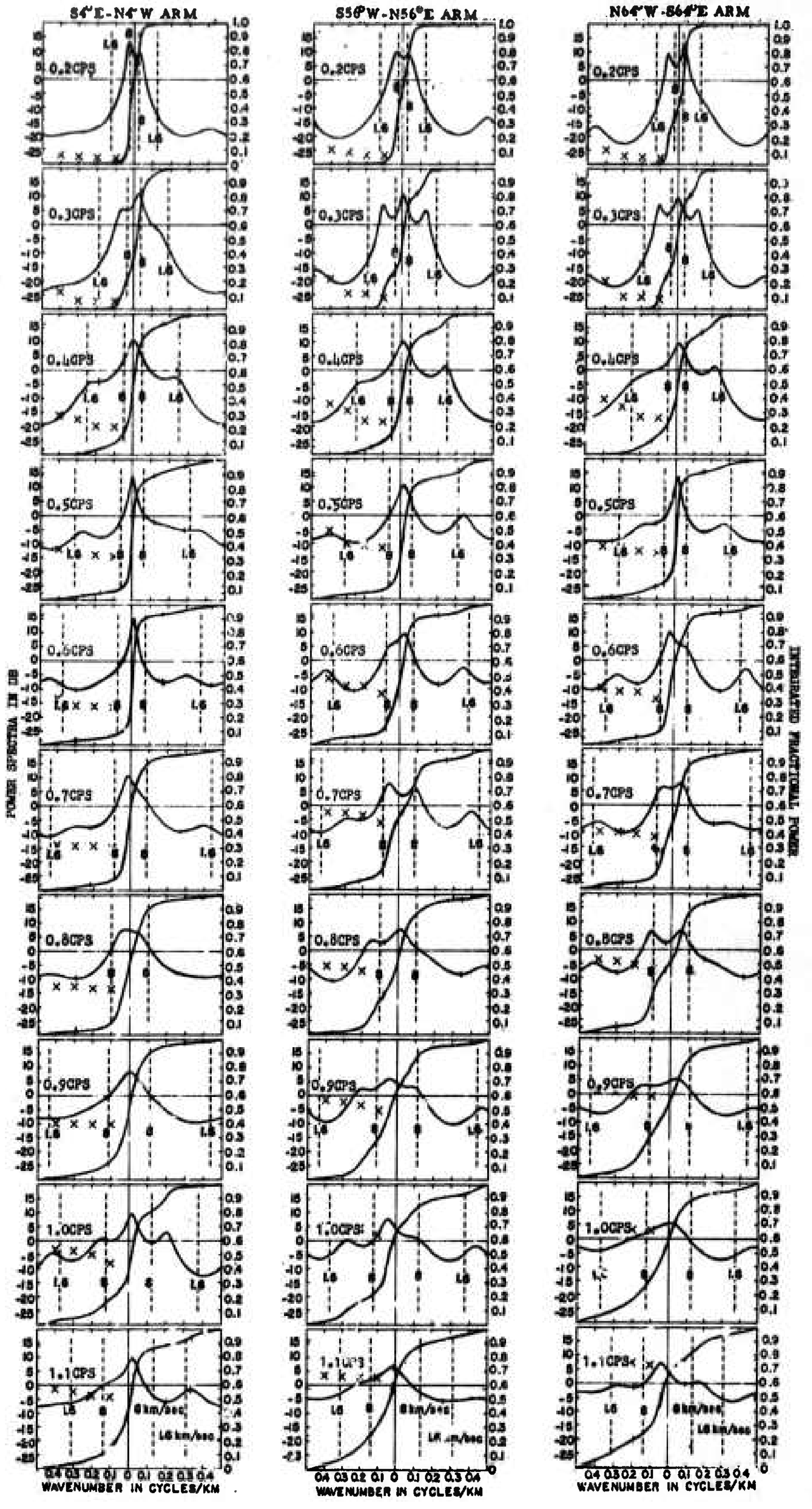


Figure III-6. Wavenumber and Integrated Spectra for Subarray A0 for 5 February 1966

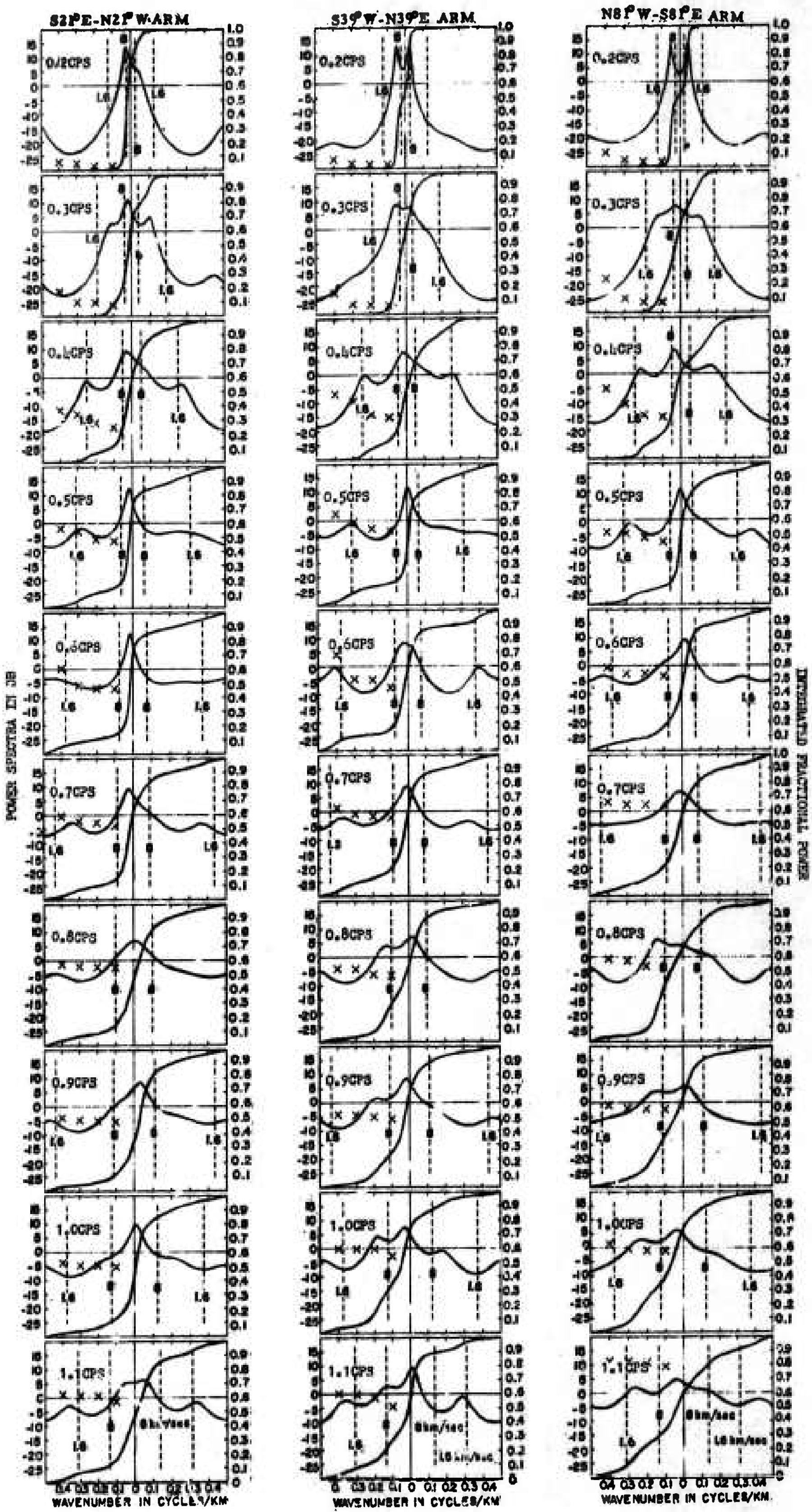


Figure III-7. Wavenumber and Integrated Spectra for Subarray F2 for 5 Febru ry 1966

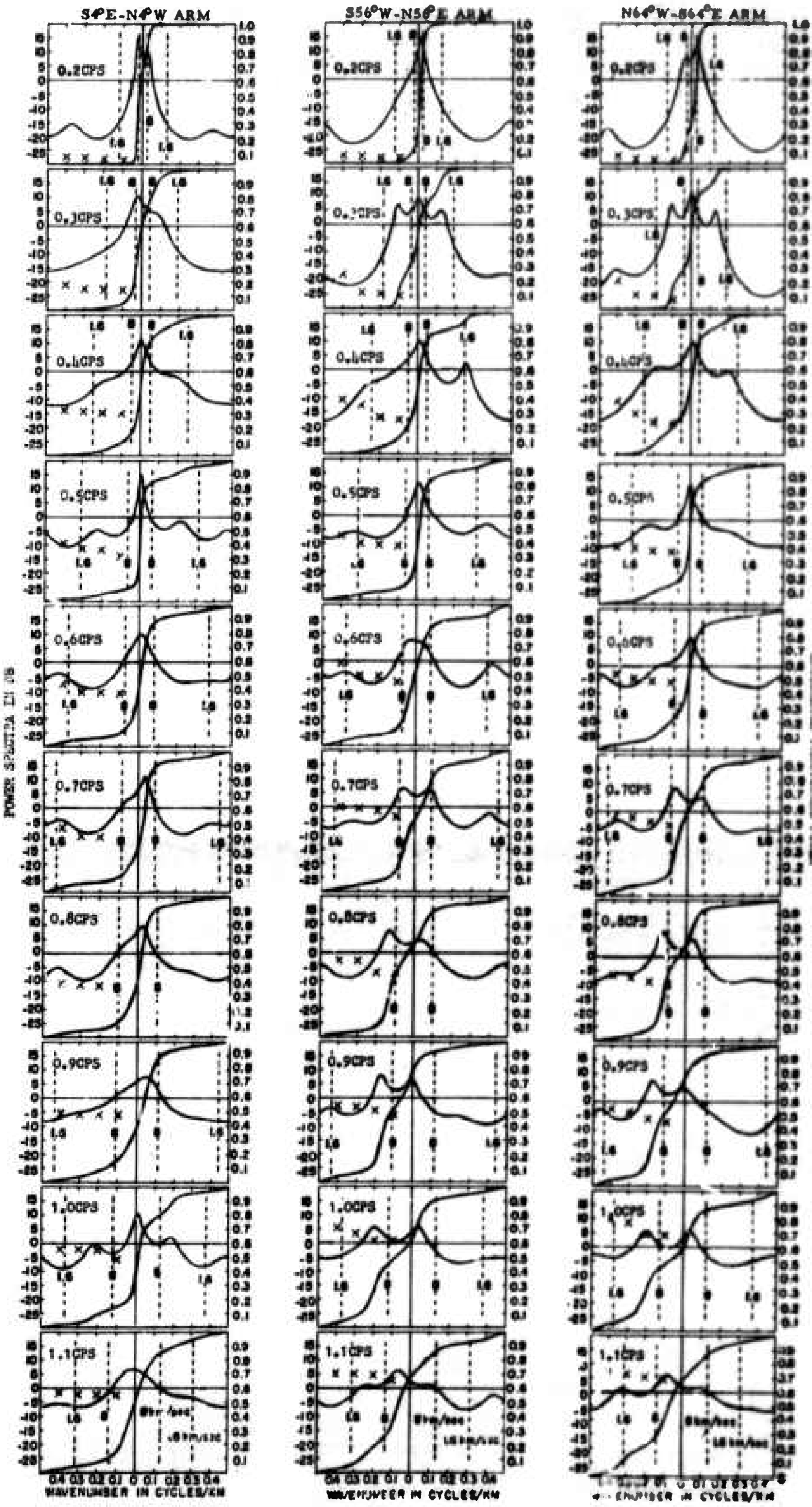


Figure III-8. Wavenumber and Integrated Spectra for Subarray A0 for 25 March 1966

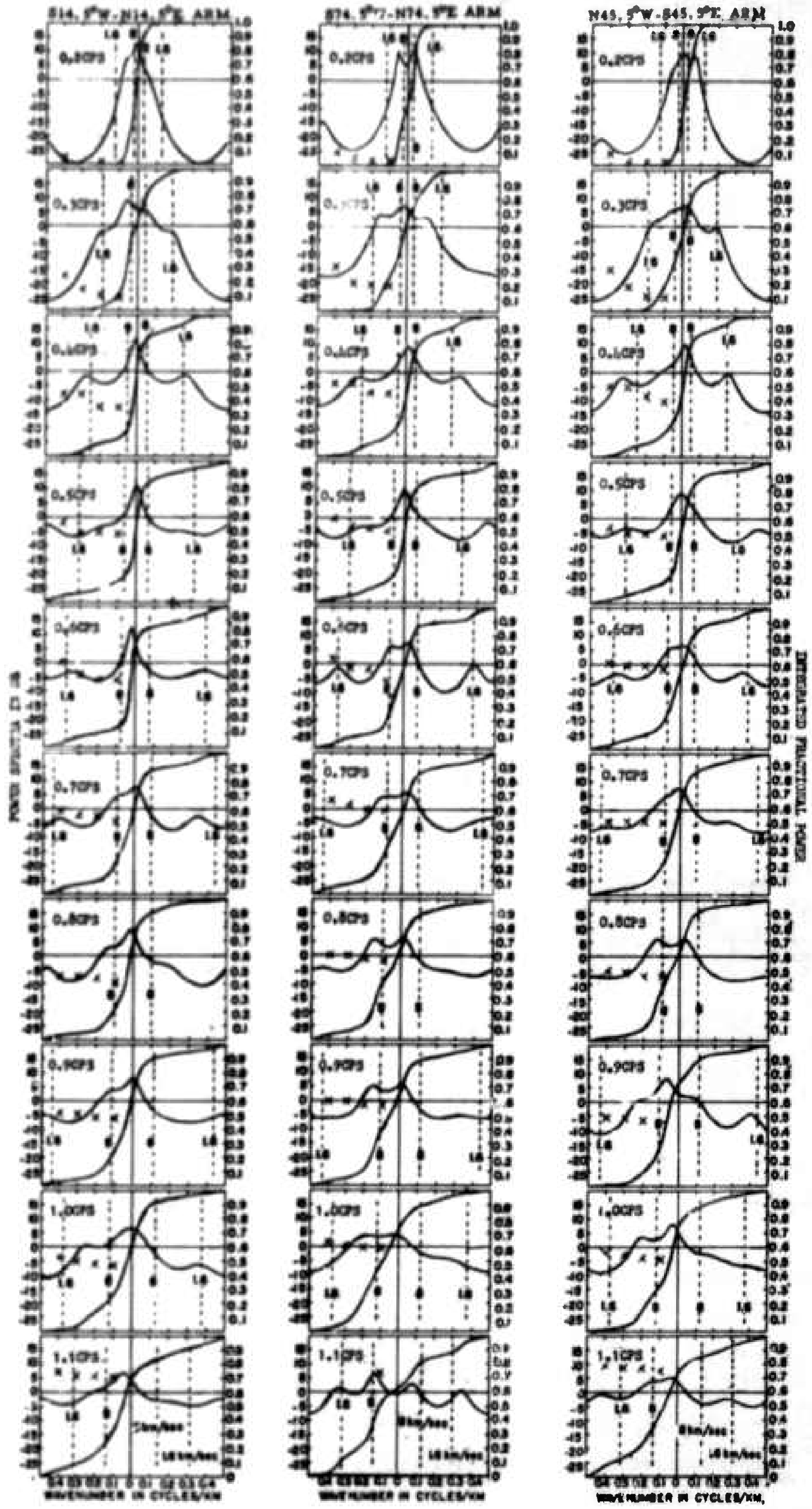


Figure III-9. Wavenumber and Integrated Spectra for Subarray F1 for 25 March 1966

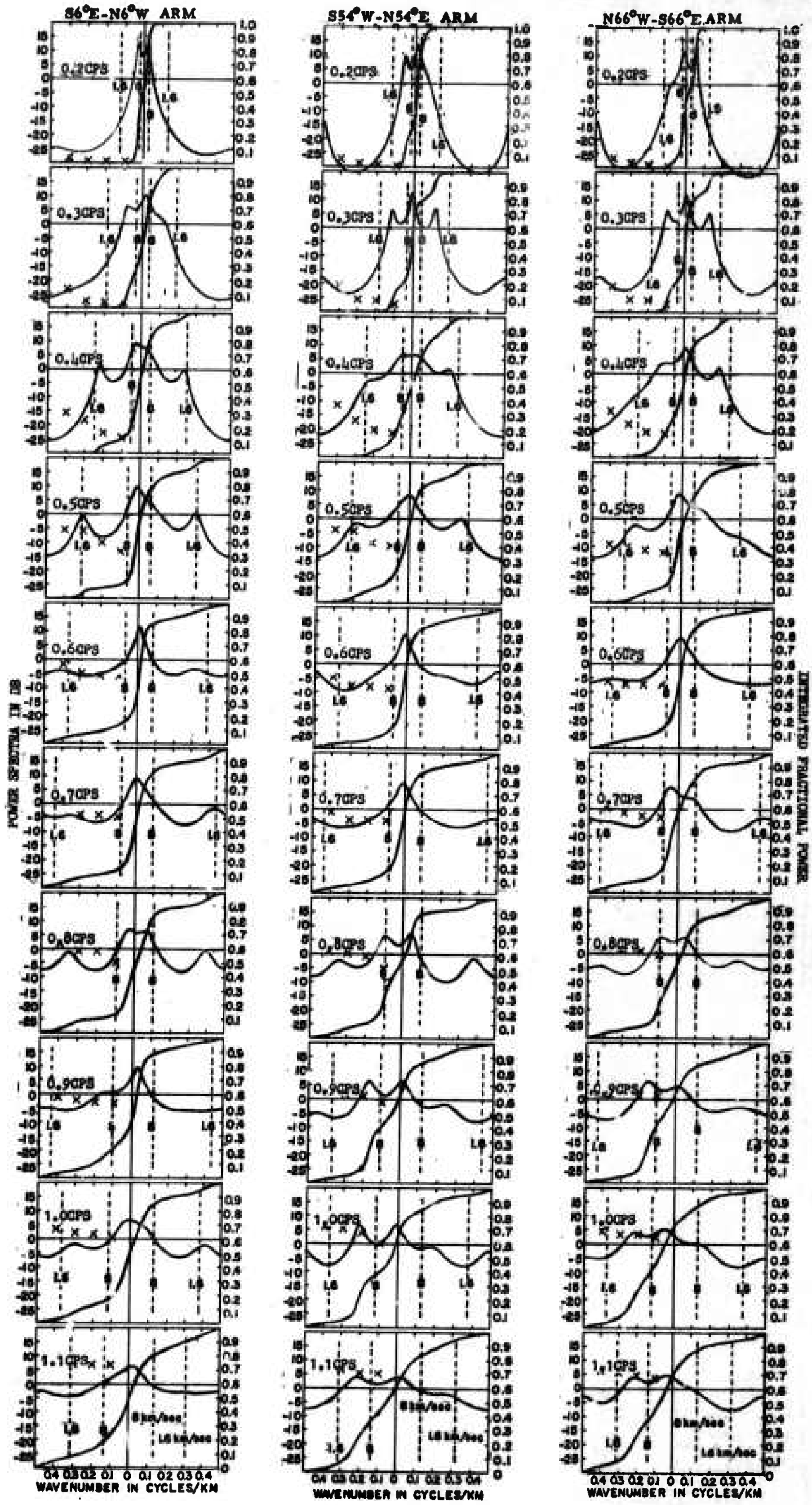


Figure III-10. Wavenumber and Integrated Spectra for Subarray F3 for 25 March 1966

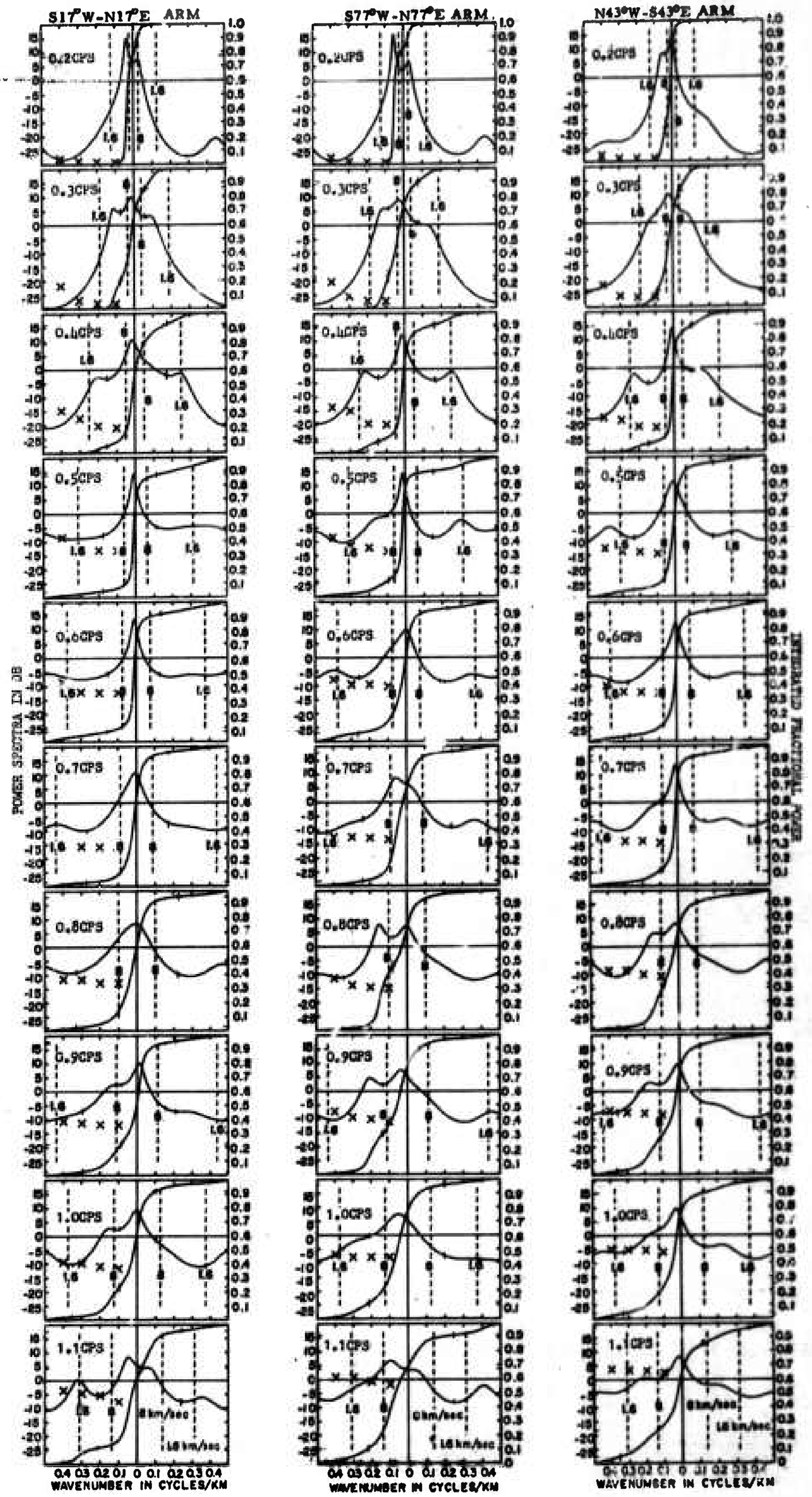


Figure III-11. Wavenumber and Integrated Spectra for Subarray B4 for 8 April 1966

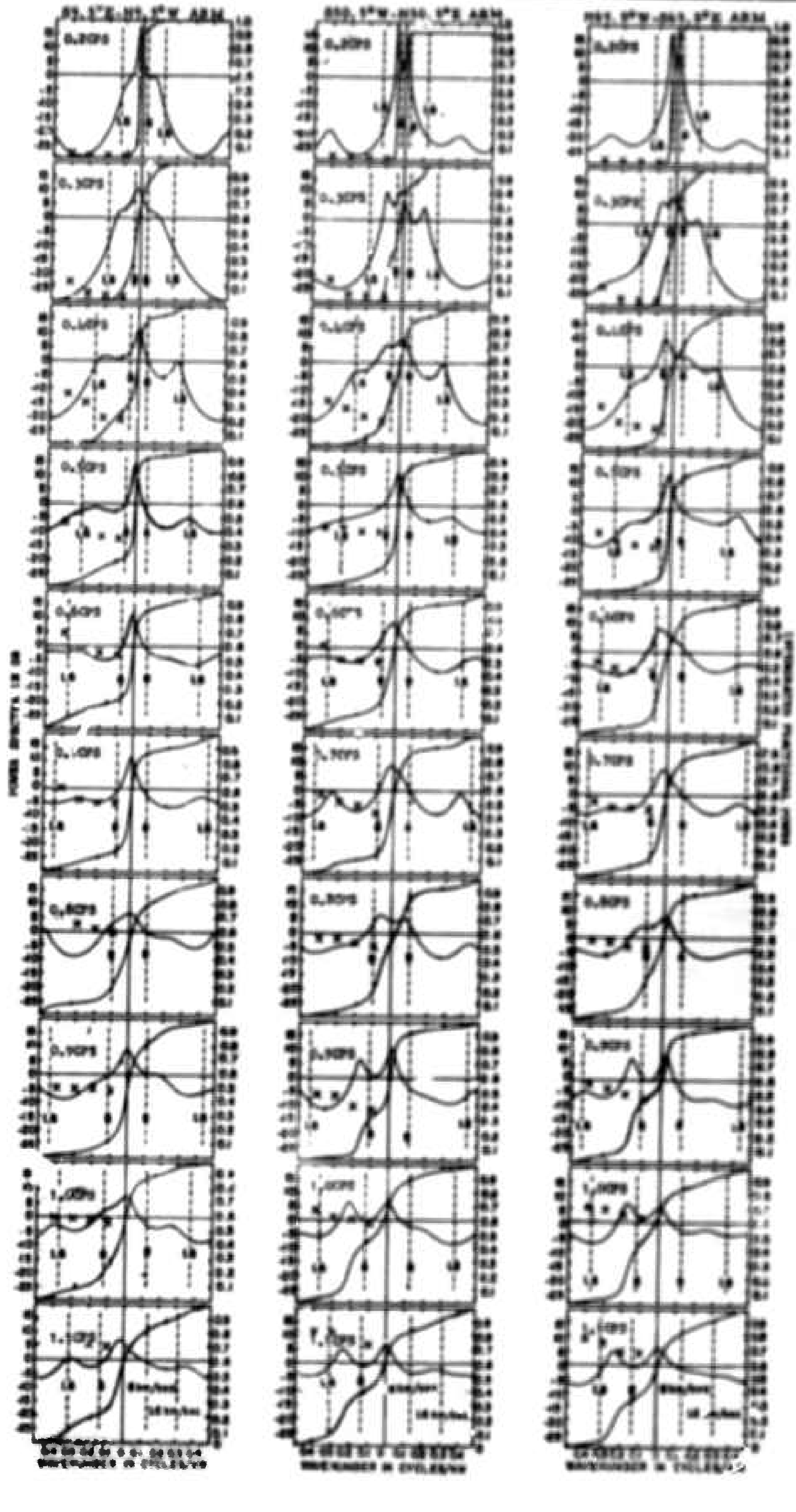


Figure III-12. Wavenumber and Integrated Spectra for Subarray F4 for 8 April 1966

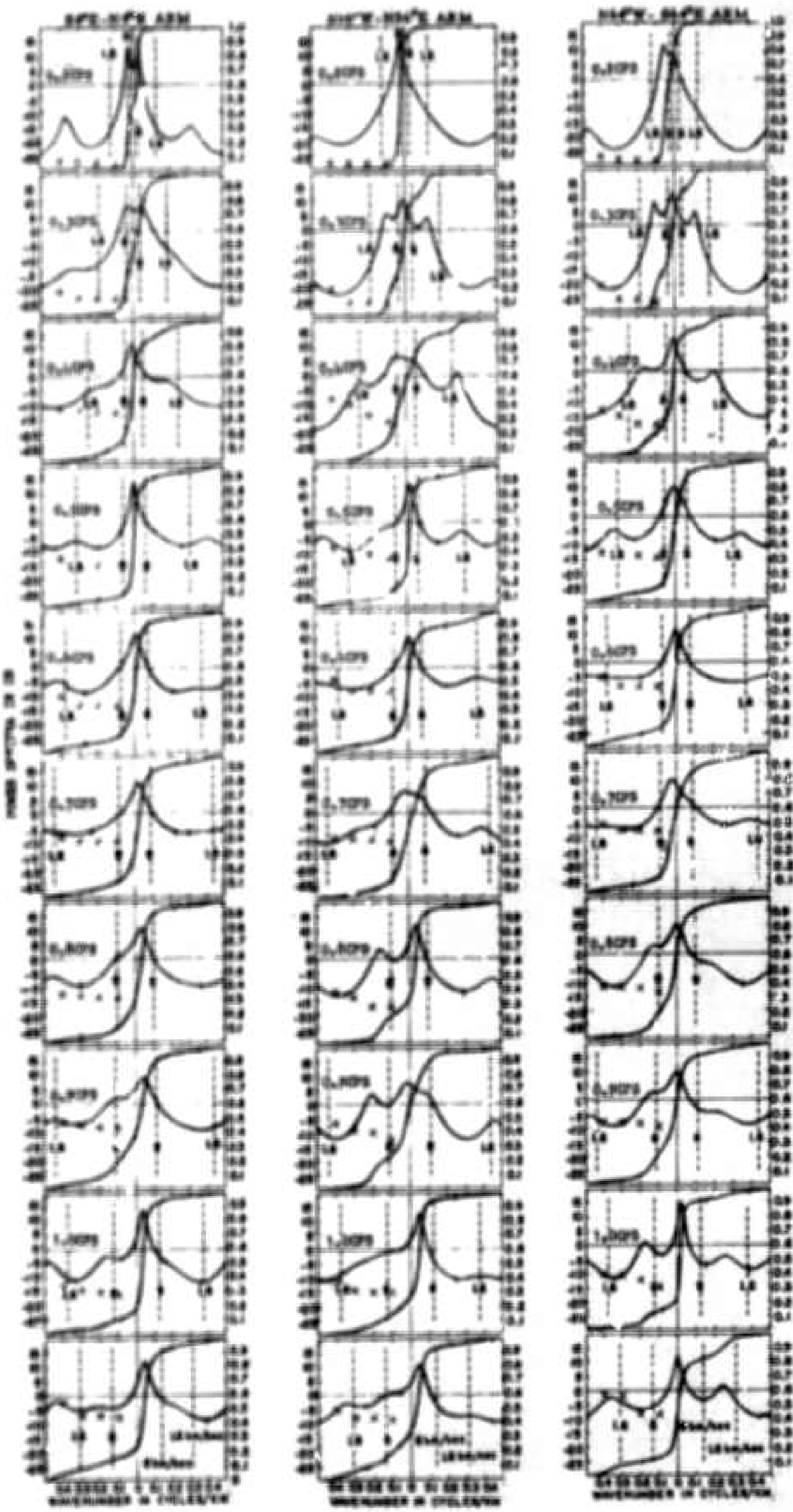


Figure III-13. Wavenumber and Integrated Spectra for Subarray A0 for 15 April 1966

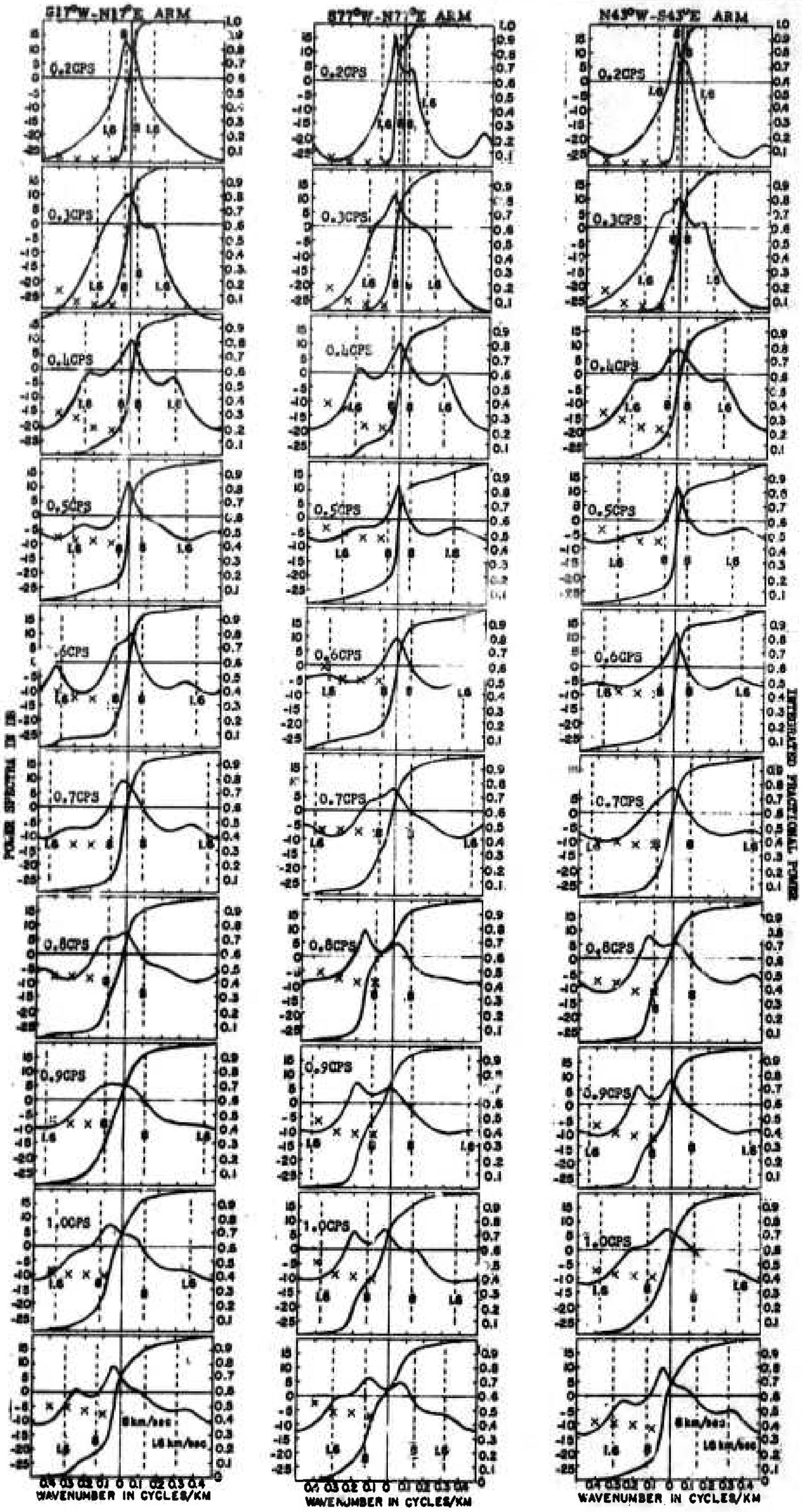


Figure III-14. Wavenumber and Integrated Spectra for Subarray B4 for 29 April 1966

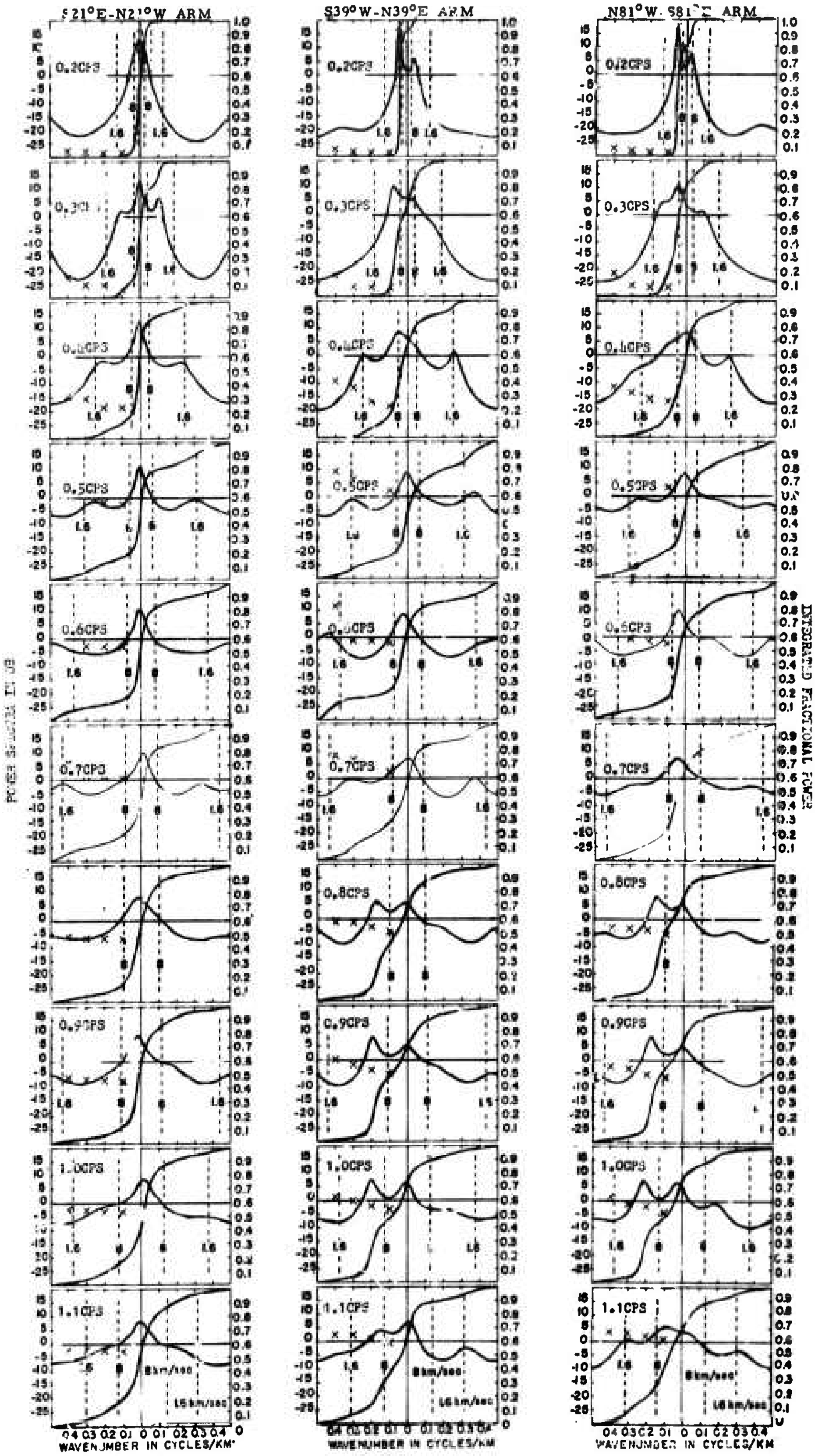


Figure III-15. Wavenumber and Integrated Spectra for Subarray F2 for 29 April 1966

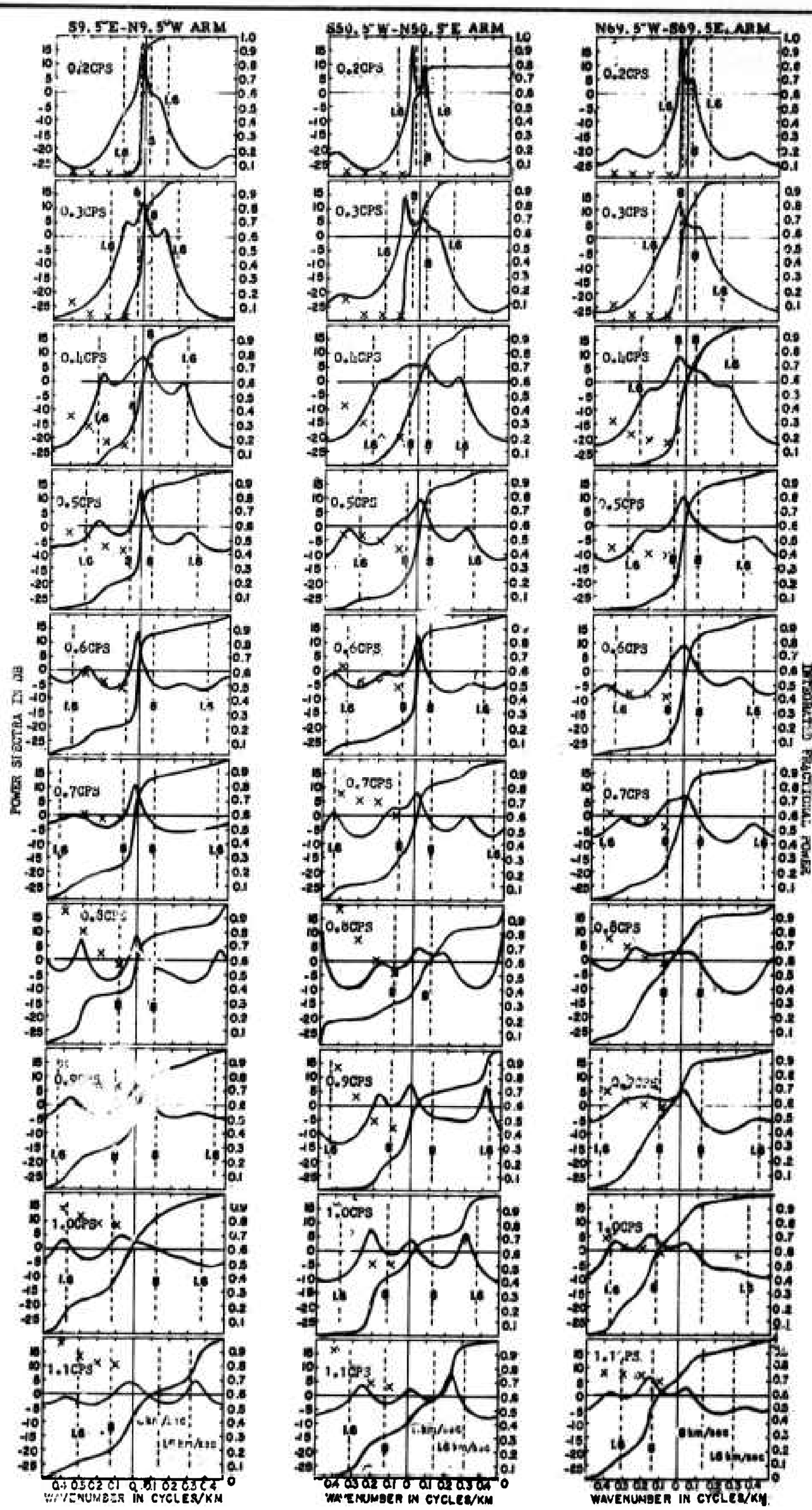


Figure III-16. Wavenumber and Integrated Spectra for Subarray F4 for 29 April 1966

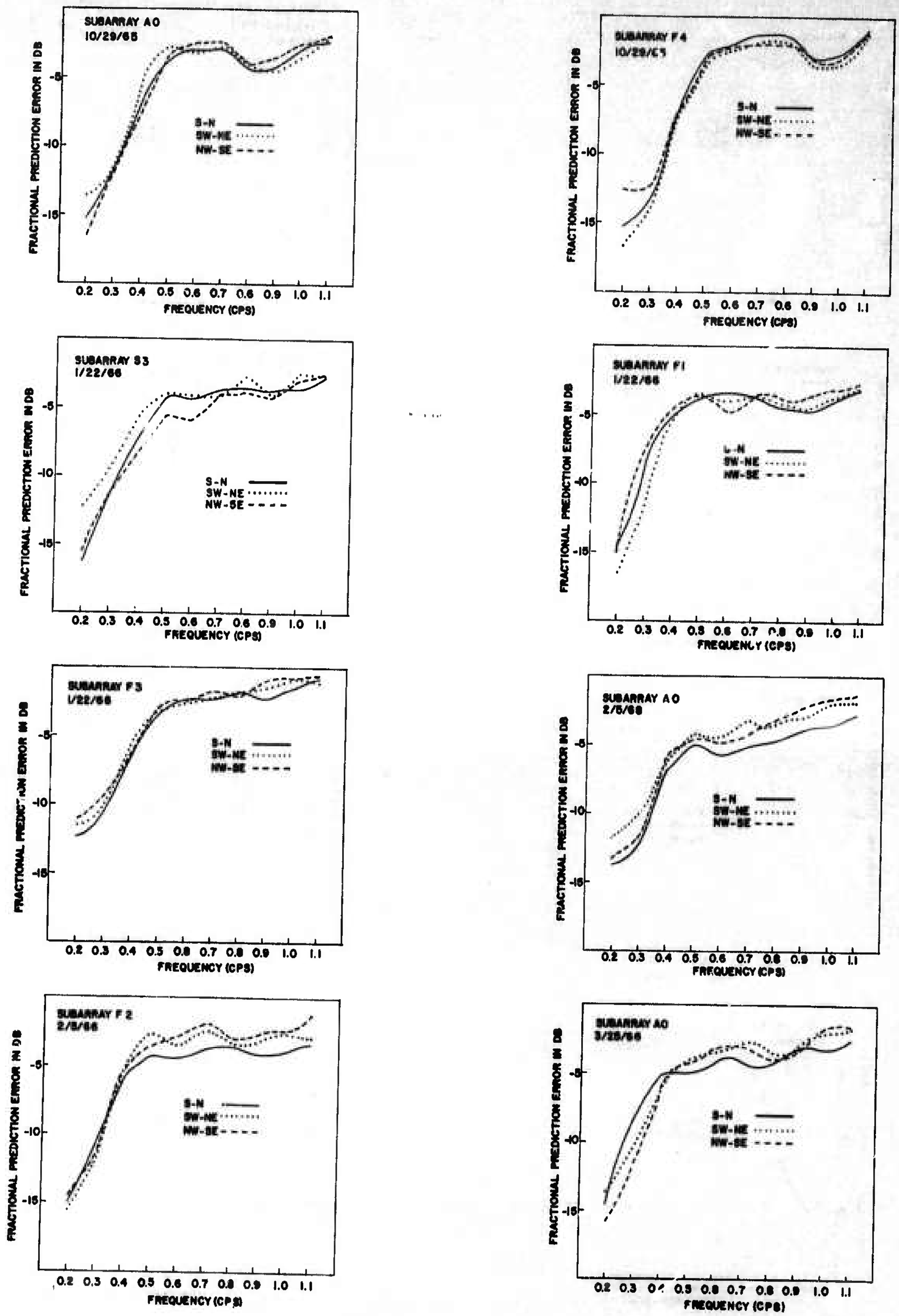


Figure III-17. Fractional Prediction Error in db vs Frequency for Predicting One Seismometer Ahead Using a Line of Four Seismometers

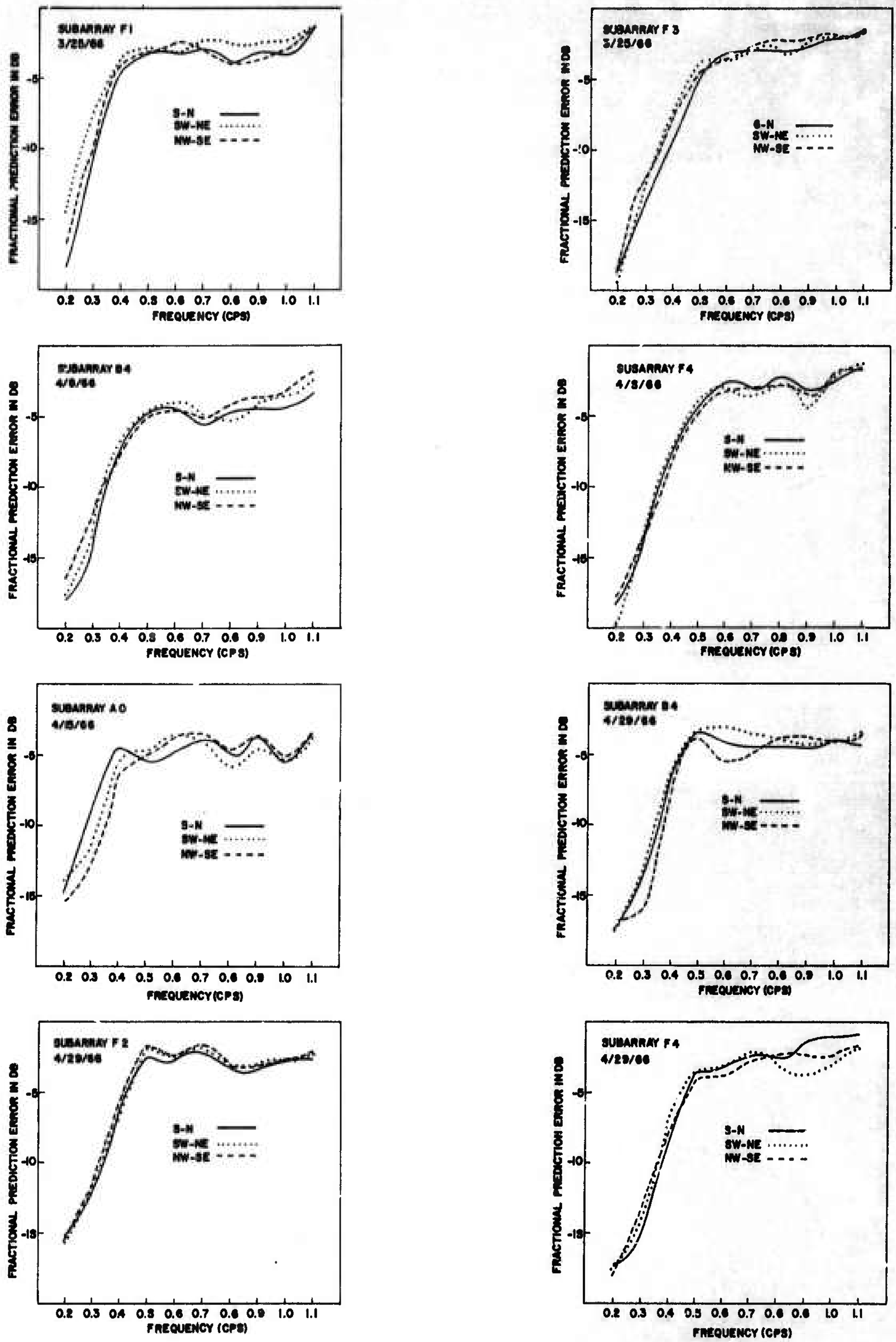


Figure III-17. (Contd)

SECTION IV
INTERPRETATION OF THE K-LINE WAVENUMBER SPECTRA

LASA ambient seismic noise components and an estimation of their frequency power spectra were obtained from the K-line wavenumber spectra by combining the information contained in the spectra of the three arms of the subarray for each frequency. Each peak in the K-line spectra corresponds to the apparent wavenumber of some wave as measured in the direction of each arm of the subarray. Lines were drawn perpendicular to the arms of the subarray at points corresponding to the apparent wavenumbers associated with each peak in the spectra. Intersection of the appropriate lines from the three arms represents the wave in K space. The wavenumber was measured from the center of the plot (0.0 cycles/km) to the intersection. In general, the line intersection was not a point but, instead, a triangle due to imperfect data and analysis. The center of the triangle was used as the estimated point of intersection of the three lines. This method of obtaining the direction and velocity of the noise source from the K-line spectra is illustrated in Figure IV-1 for the spectra of subarray F4 at 0.2 cps (Figure III-2).

Figure IV-2 contains the estimated frequency power spectra of the ambient seismic-noise components as determined by the K-line spectra for seven noise samples. These estimates are shown after they were combined with the absolute frequency spectra of the total noise. In most cases, estimates of the power were calculated only from the density function of the arm along which the energy was most clearly separated in the spectra.

Two low-velocity ($V < 8.0$ km/sec), fairly time-stationary, directional noise modes were very apparent in the K-line spectra of all noise samples. One mode was present at 0.2 cps only, and the other was evident in the frequency range 0.8 cps to 1.1 cps.

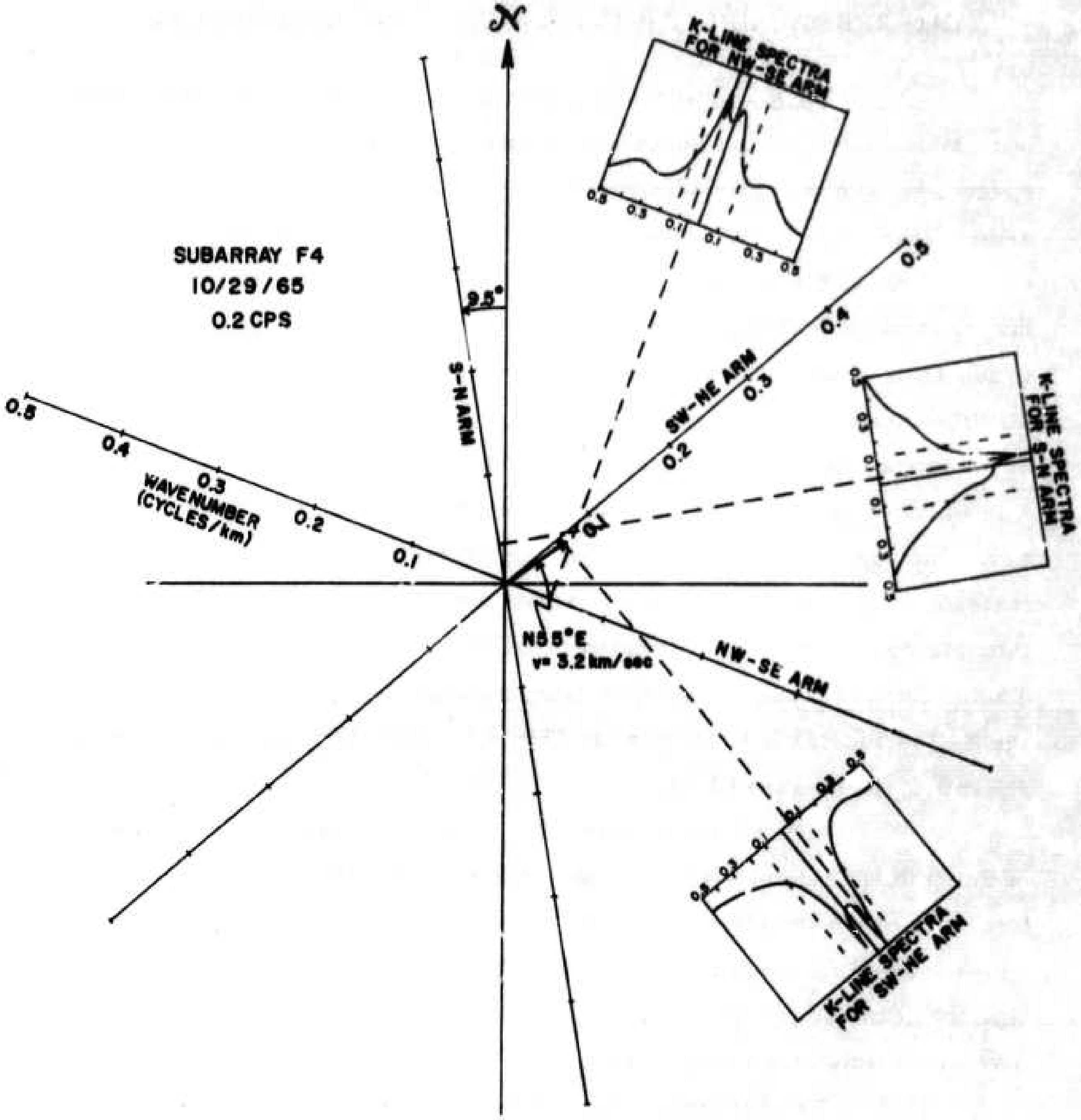


Figure IV-1. Method of Obtaining Possible Direction and Velocity of Noise Mode at 0.2 cps for Noise of 29 October 1966

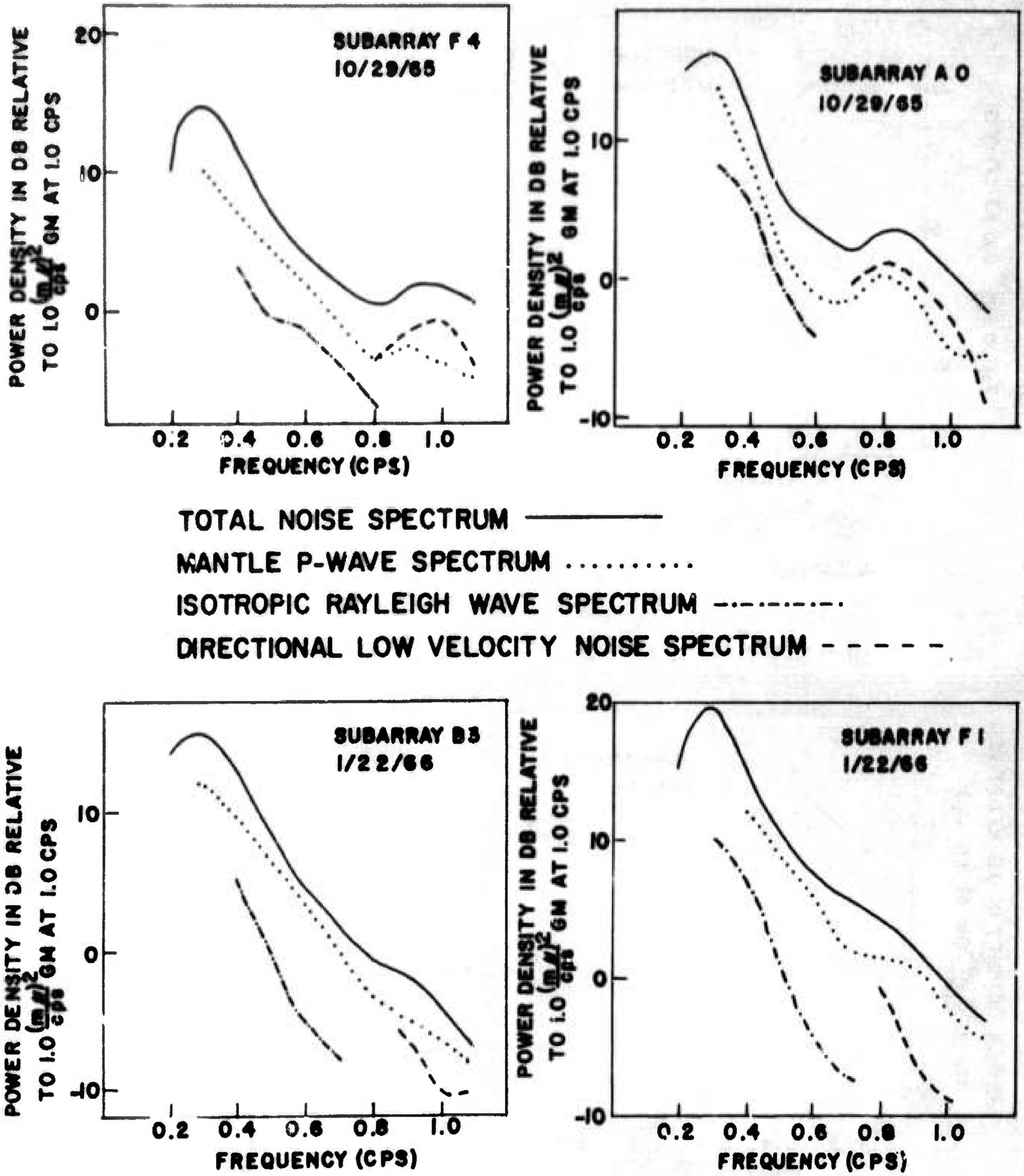


Figure IV-2. Estimated Frequency Power Spectra of Three Noise Components of LASA Ambient Noise

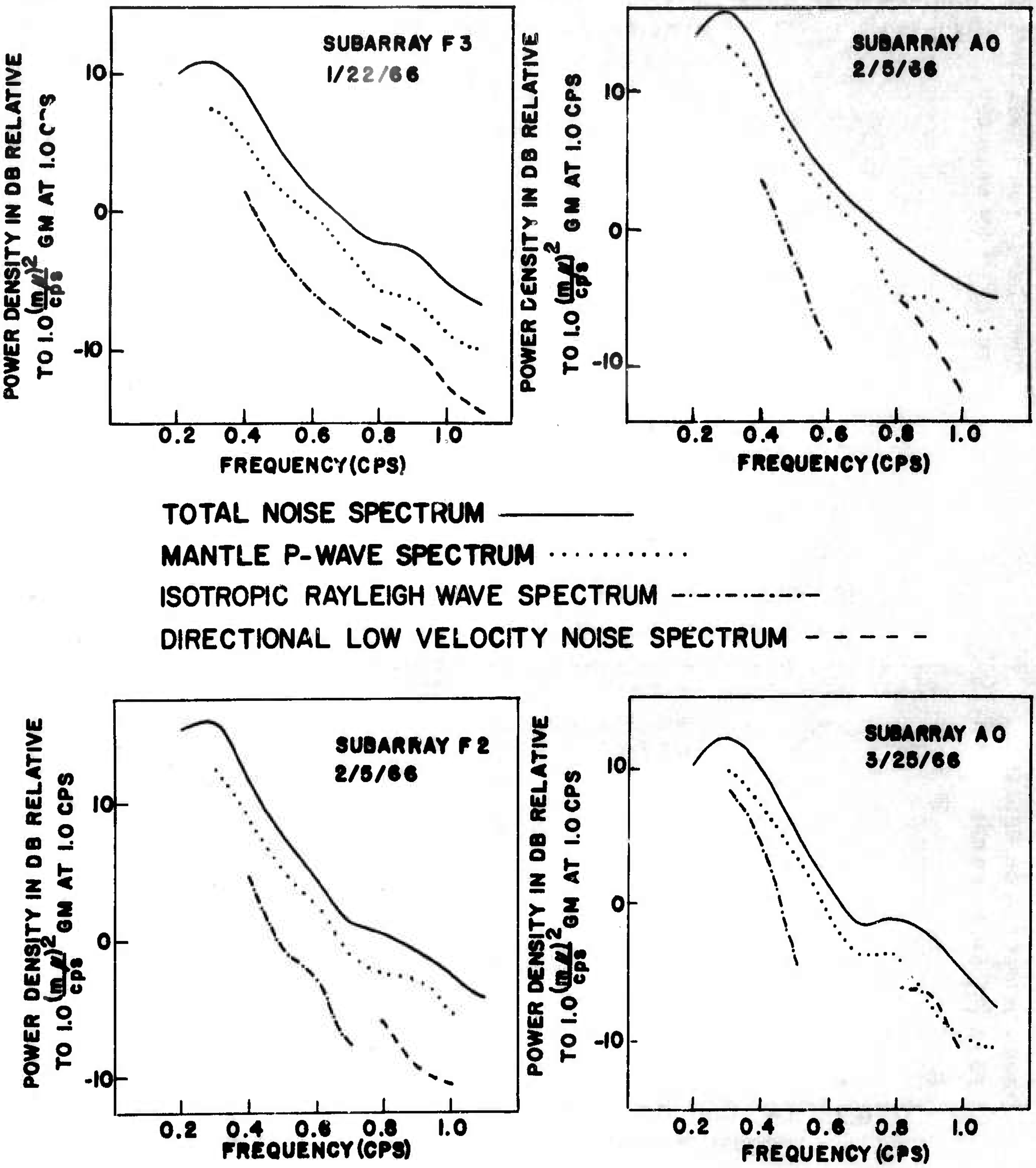


Figure IV-2. (Contd)

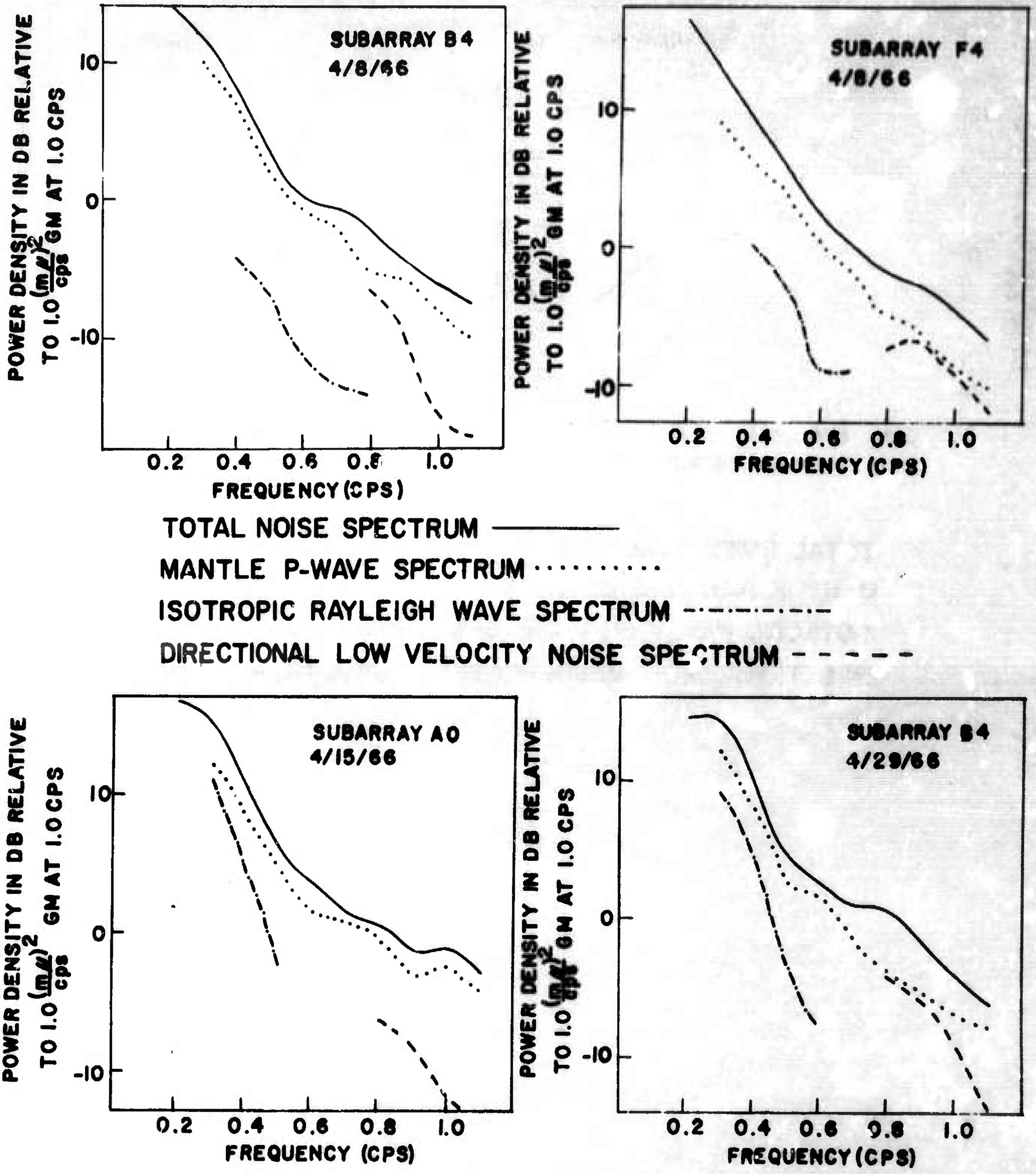
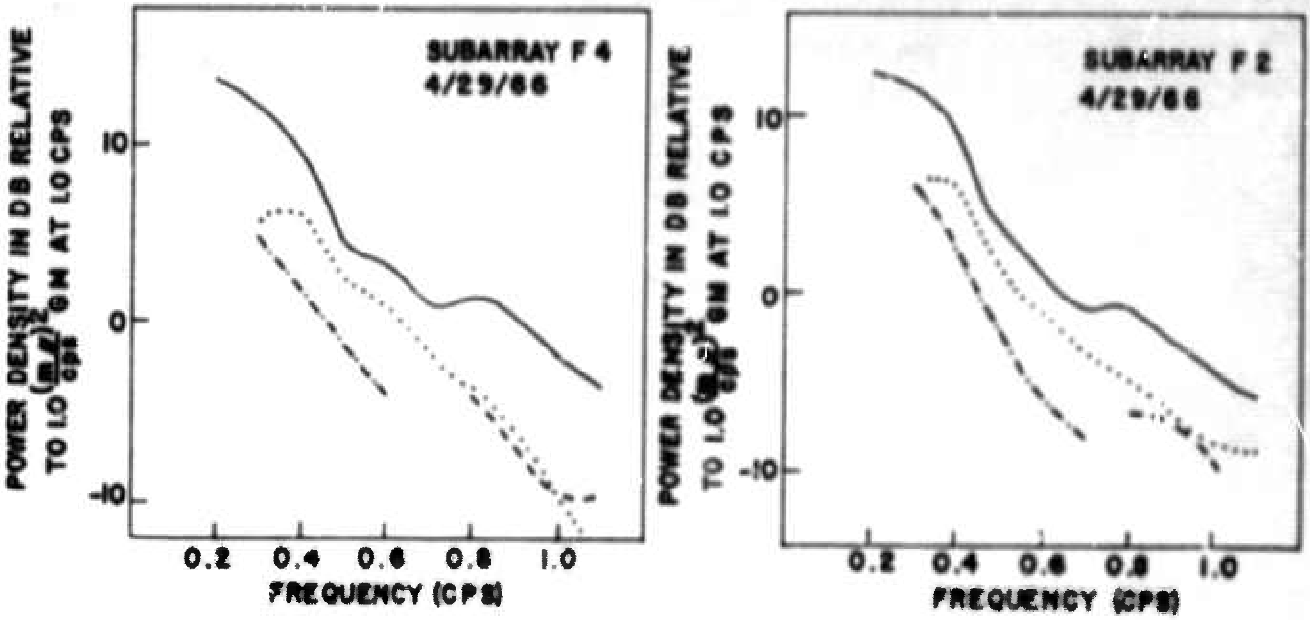


Figure IV-2. (Contd)



TOTAL NOISE SPECTRUM ————

MANTLE P-WAVE SPECTRUM ....

ISOTROPIC RAYLEIGH WAVE SPECTRUM -·-·-·-·-

DIRECTIONAL LOW VELOCITY NOISE SPECTRUM - - - - -

Figure IV-2. (Contd)

Resolution of the spectra at 0.2 cps was quite good, and fair estimates of noise direction and velocity were obtained. The low-velocity mode at this frequency constituted, on the average, about 50 percent of the total noise power. Direction of arriving waves varied from N42°E to N83°E, and phase velocity generally ranged from 3.0 to 4.0 km/sec. Table IV-1 contains the velocity and direction of this energy for all noise samples. (This noise mode was not present in the K-line wavenumber spectra of subarray F1 for the noise sample of 22 January 1966 and subarray A0 for the noise sample of 25 March 1966.) This velocity range indicates the presence of a higher order surface mode, since—according to theoretical LASA dispersion curves[3] (Figure IV-9)—the velocity of the fundamental Rayleigh mode at 0.2 cps is only about 2.5 km/sec.

A possible generator of this directional surface mode is wave activity along the Newfoundland-New Brunswick coast. No hypothesis as to why the fundamental Rayleigh mode is absent is suggested. It is noted, however, that the fundamental surface mode has been observed from such wave activity at Tonto Forest Observatory.[1]

No organized, low-velocity noise lobe was evident in the conventional wavenumber spectrum at 0.2 cps, discussed earlier in this report. Probably, the resolving power of the conventional spectra was insufficient to indicate both P-wave and surface-mode peaks at this frequency.

At higher frequencies (f >0.7 cps), there is better agreement between conventional and high-resolution spectra. Analysis of the conventional spectra indicated possible lower-velocity modes (V<8.0 km/sec) propagating roughly east to west across the array. Also, previous results[4] of wavenumber spectra of two May 1965 noise samples for subarrays Angela (B 1) and Hysham (F 3) revealed the presence of this energy. Estimated velocity range was 4.0 to 8.0 km/sec.

Table IV-1

DIRECTION AND VELOCITY OF LOW-VELOCITY SURFACE MODE AT 0.2 cps FOR ALL NOISE SAMPLES

Noise Sample	Subarray	Direction of Source	Velocity of Noise Mode (km/sec)
29 October 1965	A0	N59°E	3.3
	F4	N55°E	3.2
22 January 1966	B3	N83°E	3.7
	F3	N54°E	4.0
5 February 1966	A0	N79°E	3.3
	F2	N53°E	3.3
25 March 1966	F1	N42°E	3.0
	F3	N45°E	3.6
8 April 1966	B4	N83°E	3.1
	F4	N60°E	4.0
15 April 1966	A0	N74°E	4.0
	F2	N49°E	4.0
29 April 1966	B4	N77°E	3.3
	F2	N74°E	3.6
	F4	N58°E	3.7

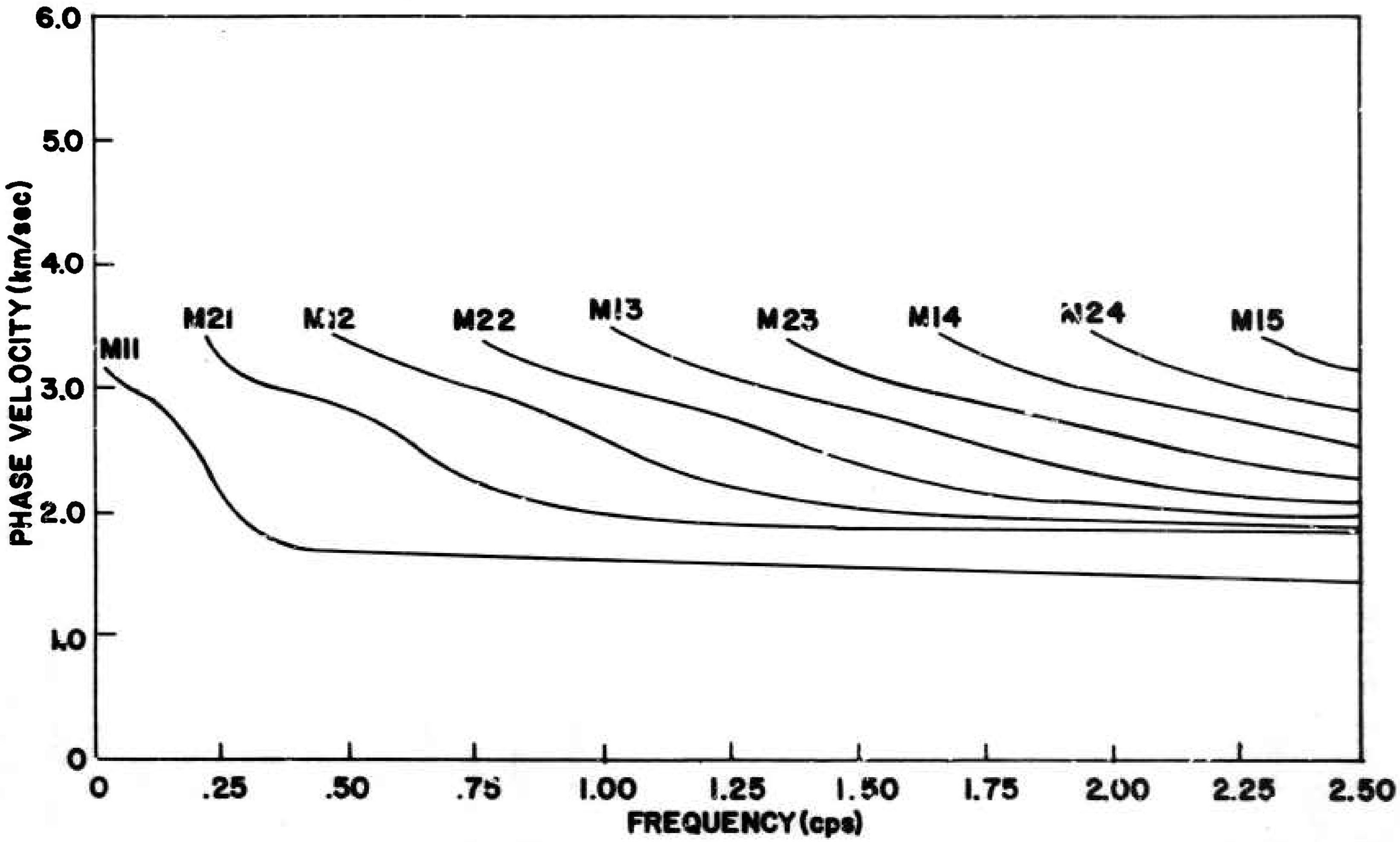


Figure IV-3. LASA Theoretical Dispersion Curves for Nine Normal Modes

This noise mode is also apparent in the 1-dimensional wavenumber spectra in the frequency range 0.8 to 1.1 cps. The organized noise pagates at approximately 4.0 to 5.0 km/sec from a northeasterly direction. Although K-line spectra were not calculated for subarrays B1 and C2 for the 25 March 1966 noise sample, K-line spectra were calculated for three other subarrays (A0, F1, F3) for this same noise sample (Figures III-8, III-9, and III-10). These spectra indicate the direction of propagation to be from an area extending N79°E to S76°E. This direction is in agreement with the due-east direction obtained from the conventional spectra measured at subarrays B1 and C2. The apparent direction and velocity of this mode as determined by the K-line spectra of each subarray for every noise sample are included in Tables IV-2 and IV-3.

An attempt was made to determine the location of this source by projecting vectors in the direction of the oncoming organized noise for all the subarrays and observing the intersection of these vectors on a map. No probable location could be determined, however, because the azimuths usually were divergent. Also, no consistent direction was associated with each subarray (Table IV-3).

These conflicting results are possibly due to one (or a combination) of three causes. One of these causes is the imperfections in the data and analysis. As discussed previously, the direction and velocity were obtained by projecting lines perpendicular to the arms of the subarray in K space at locations on the arms corresponding to the apparent wavenumber of the noise mode. At these higher frequencies (0.8 to 1.1 cps), either the noise mode was separated in the spectra of two of the three arms or the intersection of the three lines was not a point but a fairly large triangle. In the latter case, the center of the triangle was used as the estimated point of intersection. A similar study at the TFO array[1] resulted in better resolution consistency. This may be due either to the arrangement of the array (TFO has 11 seismometers in line, whereas a LASA subarray has only five) or to the length of the data (the TFO study used a 20-min noise sample, and this study investigated 7-min noise samples).

Table IV-2

RANGE OFAZIMUTH AND VELOCITY OF THE ORGANIZED, LOW-VELOCITY NOISE IN FREQUENCY RANGE 0.8 TO 1.0 cps

Noise Sample	Subarray	Azimuth Range	Velocity Range (km/sec)
29 October 1965	A0	N54°E-N62°E	3.6-4.3
	F4	N30°E-N47°E	4.4-5.0
22 January 1966	B3	S84°E-S89°E	3.8-4.0
	F1	N67°E-N87°E	3.8-4.5
	F3	N51°E	4.2
5 February 1966	A0	N70°E-N75°E	4.6-5.4
	F2	N55°E-N80°E	4.1-5.0
25 March 1966	A0	N86°E-S88°E	4.4-5.5
	F1	S76°E-S81°E	4.6-5.0
	F3	N79°E-N84°E	4.0-4.8
8 April 1966	B4	N78°E-N81°E	3.2-3.7
	F4	N70°E-N80°E	4.5-4.7
15 April 1966	A0	N63°E-N74°E	4.3-4.9
	F2	N62°E-N71°E	4.5-4.6
29 April 1966	B4	N46°E-N50°E	4.2-4.7
	F2	N65°E-N74°E	4.2-4.3
	F4	N61°E-N82°E	4.3-4.5

Table IV-3

RANGE OF AZIMUTH AND VELOCITY WITHIN SUBARRAYS OF THE LOW-VELOCITY NOISE IN FREQUENCY RANGE 0.8 TO 1.0 cps

Noise Sample	Subarray	Azimuth Range	Velocity Range (km/sec)
29 October 1965	A0	N54°E-N62°E	3.6-4.3
5 February 1966		N70°E-N75°E	4.6-5.4
25 March 1966		N86°E-S88°E	4.4-5.5
15 April 1966		N63°E-N74°E	4.3-5.9
8 April 1966	B4	N78°E-N81°E	3.2-3.7
29 April 1966		N46°E-N50°E	4.2-4.7
22 January 1966	F1	N67°E-N87°E	3.8-4.5
25 March 1966		S76°E-S81°E	4.6-5.0
5 February 1966	F2	N55°E-N80°E	4.1-5.0
15 April 1966		N62°E-N71°E	4.5-4.6
29 April 1966		N65°E-N74°E	4.2-4.3
22 January 1966	F3	N51°E	4.2
25 March 1966		N79°E-N84°E	4.0-4.8
29 October 1965	F4	N30°E-N47°E	4.4-5.0
8 April 1966		N70°E-N80°E	4.5-4.7
29 April 1966		N61°E-N82°E	4.3-4.5

Another possible cause of divergent azimuths is that the source may be a diffuse source such as a river. The LASA array is bounded on the east and northeast by the Yellowstone and Missouri rivers. Local crustal variations may be another cause. LASA is situated on a shale foundation, which is notoriously anisotropic and variable.

Even though this noise source is unidentified, it is known to be time-stationary and traveling from the northeast with a horizontal velocity between 4.0 and 5.0 km/sec. At 0.8 cps, this mode constitutes between 25 and 35 percent of the total power. Estimates of the frequency power spectra of this energy are shown in Figure IV-2. A comparison of the estimated spectra of each noise sample revealed that the spectra generally differ by 2.0 to 4.0 db between subarrays within each noise sample. The most consistent spectra are those of the noise samples of 5 February and 29 April, each of which differs by less than 1 db in the frequency range 0.8 to 1.1 cps. When the spectra were compared to determine their consistency in time, the difference between spectra generally was about 1.0 to 3.0 db.

Another major constituent of the ambient noise is low-velocity (1.3 to 2.0 km/sec) isotropic Rayleigh energy. Presence of this isotropic energy is indicated in the K-line spectra by shoulders on each arm.[1] This energy is generally present in the frequency range 0.3 to 0.7 cps. Dispersion of the isotropic surface-mode energy is evident in the K-line spectra. Some variation among noise samples and subarrays exists; but above ~ 0.4 cps, the velocity generally is approximately 1.6 km/sec, which agrees with theoretical dispersion curves[3] shown in Figure IV-3.

Power spectra of this energy are included in Figure IV-2. These estimates represent the amount of power contained in the shoulders of the K-line spectra and were obtained from the integrated wavenumber power-density function. Spectra for the same subarray but for different noise samples differ by about 1.0 to 4.0 db in the frequency range 0.4 to 0.7 cps. Generally, at 0.4 cps, the isotropic energy contributes about 24 percent of the total noise power.

A strong contribution to the total noise comes from high-velocity energy. The mantle P-wave noise was estimated from the K-line spectra by taking the energy above the "white" background with horizontal velocity greater than 8.0 km/sec. In obtaining estimates of the mantle P-wave spectra, the fact that broadside Rayleigh energy contributes to the amount of apparent high-velocity energy was considered. The power of the mantle P-wave noise generally predominates for all frequencies greater than 0.3 cps and less than 1.0 cps. At higher frequencies (1.0 and 1.1 cps), the energy appears to be essentially uncorrelated.

Estimates of the mantle P-wave energy are generally less than 3.0 db below the total noise spectrum in the frequency range 0.3 to 0.6 cps. Between 0.6 and 1.1 cps, the P-wave spectrum usually is 3.0 to 5.0 db below the total spectrum. Results from other array sites indicate that the level of coherent mantle P-wave energy falls rapidly with frequency and cannot be detected as spatially orgainzed noise at frequencies much greater than 1.0 cps. The limited resolution of the array again precludes any reliable estimate of average velocity and direction of this energy.

The estimated P-wave spectra have variations in time of 1.0 to 3.0 db in the frequency range 0.3 to 0.8 cps for four of the five subarrays investigated. Subarray F3 spectra differed by as much as 6.0 db in this frequency range. For frequencies between 0.8 and 1.0 cps, the variation between spectra usually was about 4.0 db.

Also, the mantle P-wave spectra were not space-stationary. The spectra for the subarrays of three noise samples varied about 1.0 or 2.0 db in the frequency range 0.3 to 1.0 cps; and for the other four noise samples, the spectra differed by as much as 5.0 db.

In view of the large signal-smplitude differences observed at LASA, these P-wave spectral differences should certainly be expected. It appears that the P-wave noise power spectra differ a great deal less (in amplitude) than signals.

Only the major components of the total noise field were investigated in this analysis. Some noise samples of some subarrays contained noise modes which were not present in the other samples or subarrays. Usually, these modes were not consistent in frequency and, therefore, were not included. One of those noise modes, however, had consistent frequency. It was present in the K-line spectra of subarray F4 for 29 April 1966 (Figure III-16). This subarray has a low-velocity surface-mode in the frequency range 0.7 to 1.1 cps. Direction of the source is consistently N45°E, and velocity range is 1.4 to 1.5 km/sec. This direction corresponds to an arm of the Fort Peak reservoir (a distance of 64 km) but not to the dam or the main part of the lake. This reservoir possibly is the source.

Investigation of the general properties of the K-line spectra showed one outstanding difference between the wavenumber spectra of subarray F1 (Figures III-4 and III-9) and the spectra of the other six subarrays investigated. At lower frequencies (especially at 0.3 cps), the apparent velocity of isotropic surface-mode energy was about 1.6 km/sec at subarray F1. However, at all other subarrays, this velocity ranged generally between 2.2 and 2.7 km/sec. This change in the spectra of subarray F1 is probably due to structural differences at F1.

In this analysis of the K-line wavenumber spectra, attempts to estimate directions or velocities were often limited by the resolution of the array. Low spectral resolutions are due to the small number of seismometers in a line. To obtain a higher spectral resolution, additional seismometers were simulated by using interpolated data. In this manner, it was possible to form 14 equally spaced data points in each arm with 0.5-km spacing. Resulting K-line wavenumber spectra for subarray F4 on 29 October 1965 are shown in Figure IV-4. Original K-line spectra for this noise sample are in Figure III-2.

As may be noted, the resulting spectra are of much higher resolution. However, when an analysis of these spectra was made, the previously discussed method to obtain direction and velocities of each noise mode still resulted in a triangular intersection. The triangles obtained for both the interpolated and the noninterpolated data were usually the same size. In other words, there was no significant improvement in accurately estimating directions and velocities of the noise modes.

An estimate of the percentage of the total noise that is mantle P-wave noise as determined by the new spectra is compared to that obtained by the previous method (Figure IV-5). Between 0.3 and 1.0 cps, the spectral estimates differ less than 1.0 db. At 1.1 cps, the spectra of the mantle P-wave noise estimated using the interpolated data are 3.2 db below the other.

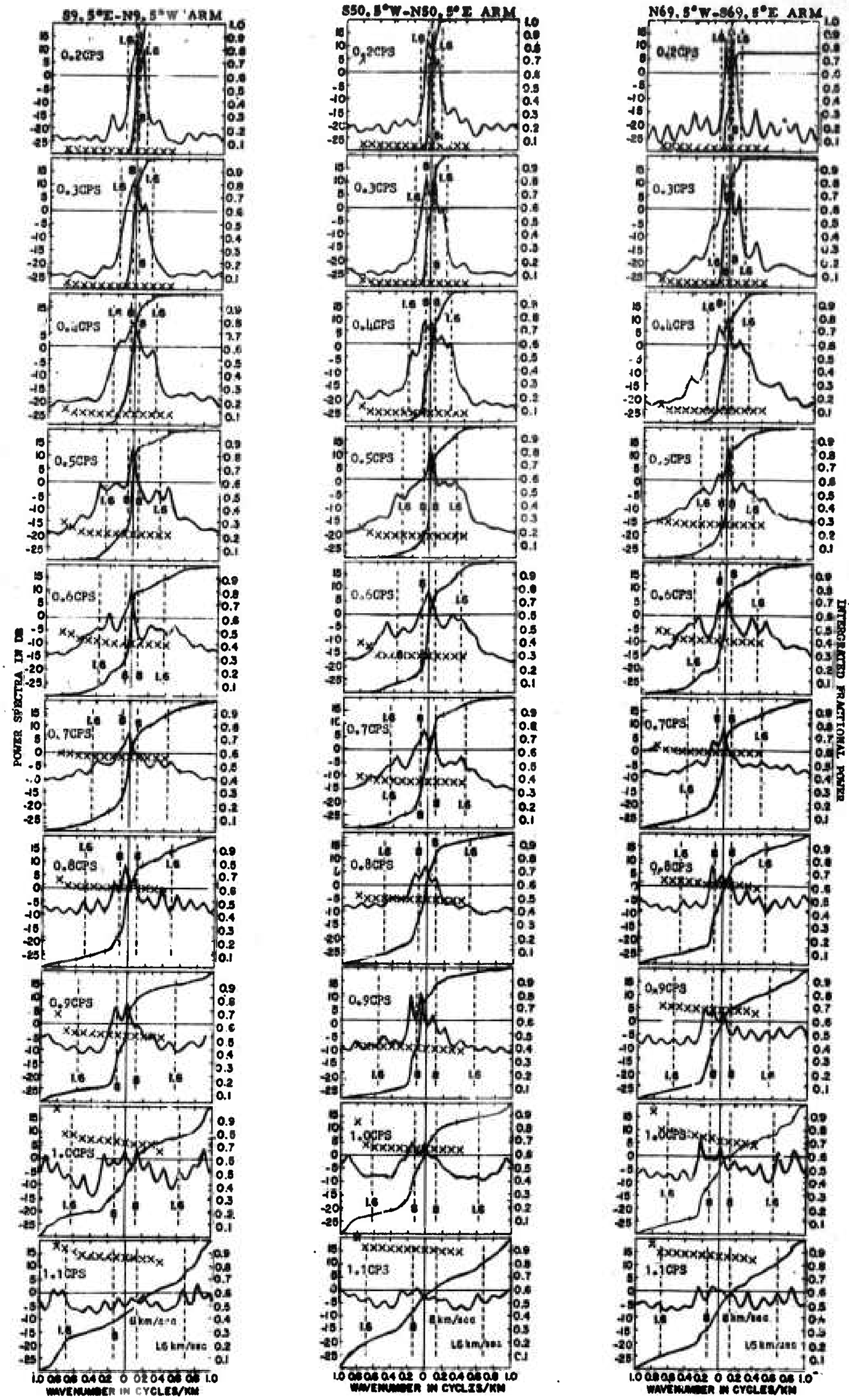


Figure IV-4. Wavenumber and Integrated Spectra for Subarray F4 Using Interpolated Data of 29 October 1966

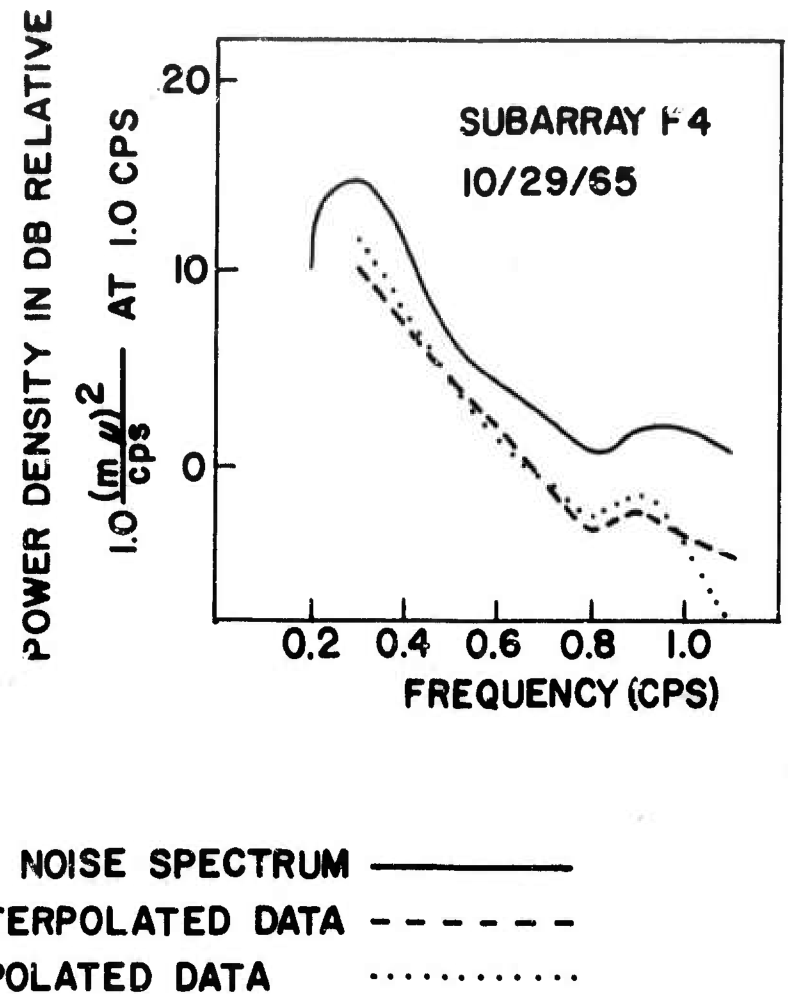


Figure IV-5. Estimated Mantle P-Wave Spectrum Using Interpolated Data of 29 October 1966 for Subarray F4

SECTION V
CONCLUSIONS

Analysis of the subarray wavenumber spectra isolated and produced estimates of the power spectra of four constituents of LASA ambient seismic noise. A higher-order surface mode traveling from an area extending N42°E to N80°E with a velocity of 3.0 to 4.0 km/sec was present at 0.2 cps. On the average, this mode constituted about 50 percent of the total noise power at this frequency. A possible generator of this directional surface mode is wave activity along the Newfoundland-New Bunswick Coast. This low-velocity energy was not present in conventional wavenumber spectra.

The 2-dimensional spectra contained an organized low-velocity noise mode at frequencies between 0.7 and 1.3 cps. The higher resolution spectra indicated that this noise propagates from the northeast at 4.0 to 5.0 km/sec. An estimate of its frequency power spectra was obtained for the frequency range 0.8 to 1.1 cps. At 0.8 cps, this mode contributed between 25 and 35 percent of the total power.

Another major constituent of the ambient noise was found to be isotropic, low-velocity (1.3 to 2.0 km/sec) Rayleigh energy. This energy is generally present in the frequency range 0.3 to 0.7 cps. Above about 0.4 cps, the velocity generally is approximately 1.6 km/sec.

Mantle P-wave energy predominates in the noise spectrum at frequencies above 0.3 cps. The P-wave component is stronger in the frequency range 0.3 to 0.6 cps. The estimated P-wave spectrum had variations with time of 1.0 to 3.0 db between 0.3 and 0.8 cps.

General features of the wavenumber spectra of subarray F1 at 0.3 and 0.4 cps were very different from the spectra of the other subarrays. At these frequencies, the apparent velocity of isotropic surface-mode energy was 1.6 km/sec at F1 but was 2.2 to 2.7 km/sec at the other subarrays. This difference in velocities is probably due to structural differences at subarray F1.

The K-line wavenumber spectra of the LASA data do not give the resolution or consistency previously obtained at TFO.[1] There are several probable causes. A LASA subarray has only five equidistant sensors in a line, whereas there are 11 in a line at TFO. Interpolated data improved the resolution of the spectra somewhat. Resulting variability probably can be controlled by using various combinations of data points.

TFO data (20 min) was longer than LASA data (7 min). The prediction error of this noise at TFO was generally 3.5 to 7.5 db less than the prediction error at LASA in the frequency range 0.3 to 0.8 cps.

It appears that the data are more precisely interpretable as seismic energy at TFO than at LASA. The most obvious difference between these two stations is that TFO is located on basement rocks, while LASA is in an area of thick cretaceous and tertiary shales. It is logical to suspect that this may be affecting the data.

SECTION VI
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13. ABSTRACT

The ambient seismic noise at LASA was studied using high-resolution wavenumber spectra obtained for several subarrays chosen from seven noise samples covering a seven month period. A comparison of the high-resolution spectra with conventional spectra measured at two subarrays for one of the noise samples was made.

Estimations of the frequency power spectra of the mantle P-wave noise and isotropic Rayleigh-wave energy were obtained. Also, estimations of the power spectra were determined for two low-velocity (V < 8.0 km/sec), fairly time-stationary, directional noise modes. One mode was present at 0.2 cps only, and the other was evident in the frequency range 0.8 to 1.1 cps.

This investigation of the ambient seismic noise revealed one outstanding difference between the characteristics of subarray F1 and the characteristics of the other six subarrays studied. At 0.3 cps the apparent velocity (1.6 km/sec) of isotropic surface-mode energy at F1 was lower than the velocity of this energy (2.2 km/sec to 2.7 km/sec) at the other subarrays.

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